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Future directions in drone routing research

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Abstract

Optimization of routing problems using drones (unmanned aerial vehicles or UAVs) has become an important area of academic research. The purpose of this article is to look to the future and help stimulate drone routing research in directions we hope will prove interesting and fruitful. We discuss opportunities for better modeling of (1) drone capabilities for both existing drones and those likely to be used in the future, (2) constraints on drone performance and operations, (3) different objectives for various drone services, and (4) alternative delivery modes, as well as some areas for methodological advances and some possible new applications. While much of the research to date has leveraged existing TSP (traveling salesman problem), VRP (vehicle routing problem), and arc routing models, we look forward to new contributions from drone research that use better models of more realistic drone types and new drone applications.

KEYWORDS
drones, future, UAVs, vehicle routing

1 | INTRODUCTION

There is a growing body of academic research on optimization for a variety of routing problems using drones (unmanned aerial vehicles or UAVs). For some reviews, see Chung et al. [11], Khoufi et al., [23], and Otto et al. [32]. Much of this research extends TSP and VRP models, though there is some work on arc routing with drones as well (e.g., [7,10]). The purpose of this article is not to summarize the rapidly growing drone routing research, but rather to raise some questions to stimulate new and better drone routing research in directions that we think will prove interesting and fruitful.

We focus on commercial uses of drones (not military) and primarily on aerial drones, rather than ground or sea drones. (We distinguish ground drones or robots as small autonomous ground vehicles, such as for home delivery, as opposed to autonomous automobiles and freight trucks.) While some models, solution methodologies, and applications for aerial drones apply to autonomous ground and sea drones, there can also be unique objectives, constraints, and features for applications of sea and ground drones [6], as well as for military applications.

To make predictions about future applications and research involving drone routing, one should consider the fundamental question of “When, where, and how should drones be used—and might drones be used?” One simple answer is that drones *should* be used in settings where they provide advantages over the alternatives, but they *might* be used in a very wide range of applications, including new ones where there are no existing alternatives. In general, the advantages of drones may be in terms of lower cost, better service, or to provide new services not previously possible. Some of these advantages necessarily stem from the removal of the human operator, especially in the areas of cost and safety. As one example, drones can eliminate the time limits imposed on human vehicle drivers as from hours-of-service regulations or from fatigue.

One perspective on drones is that they simply represent an alternative transport mode, albeit with specific capacity, range, cost and performance characteristics, and therefore existing vehicle routing models are applicable and extendable to drones. An alternative perspective is that drones represent a disruptive technology that has new capabilities to provide novel services, and therefore new routing models are needed. The first perspective leads naturally to extending existing optimization models for the VRP, arc routing, location-routing, etc. to incorporate drones, and impressive progress has been made along these lines (see

FIGURE 1 Quadcopter. Source: https://www.zdnet.com/article/ups-matternet-launch-drone-healthcare-delivery-service/ [Color figure can be viewed at wileyonlinelibrary.com]

[11]). The second perspective is more exciting, but more challenging, as novel uses for drones may lead to new and difficult route optimization problems. Some of the proposed novel uses for drones may prove practical; others may not. However, we do not discourage this line of thinking, as technological advances, including for batteries, may well create future realities that can be only modeled today. That being said, one should still be mindful of the technical, economic, and behavioral considerations surrounding large-scale use of drones.

2 | APPLICATIONS AND DRONE TYPES

Key network routing applications for drones include node routing (as for delivery problems) and arc routing (as for inspection of infrastructure such as pipelines and railroads, or surveillance along borders). Fast home delivery by drones has been an elusive goal (since the announcement by Amazon in 2013), but this remains a potentially very important and lucrative application. Interestingly, the most recent delivery drones announced by Amazon and Project Wing (a subsidiary of Alphabet Inc.) are hybrid drones that are substantially larger and different from the original delivery drone proposed by Amazon in 2013 [33]. This shows the rapid pace of change in drone design due to a myriad of considerations including technology, safety, reliability, etc. A number of drone applications, such as agricultural sensing and crop spraying, search, surveillance, etc., fall into the category of area coverage problems, and these can be converted to network problems by identifying a network that provides coverage of the region [28]. Such coverage typically is represented using an aerial footprint (e.g., circular or rectangular) of a sensor or for dispersal of fluids (as in crop spraying). A novel search application is using underwater drones to detect minerals on the ocean's floor; a market potentially worth trillions of dollars [19].

It is not surprising that some of the earliest and most promising applications of drones to date have been in closed private systems (e.g., crop treatment and infrastructure monitoring) and where alternatives are poor and/or the need is critical. Health-care, especially in regions of developing countries that lack reliable transportation [31,35] is an important application area, as the critical needs for medical supplies (blood, vaccines, medicines, etc.) create a natural opportunity for drone delivery. Further, cold chain requirements for some medicines (e.g., keeping the medicine between 2° and 8°C) provide another advantage for the faster delivery provided by drones. Drone delivery of medical supplies in urban regions is also being tested, for example to deliver medical supplies and defibrillators [12,16,39], where the drone can provide quicker delivery (especially in areas with high levels of road traffic congestion) that may result in significant improvements in health outcomes. Another promising idea for drone delivery involves regions with unique geographic challenges, such as islands and mountainous areas ([3,14]).

There are many different types of drones available—and there will certainly be new types of drones in the future. (As we limit ourselves to drones for commercial applications, we ignore the impressive capabilities and accomplishments of military drones.) Typical rotorcopter drones (often with 4, 6, or 8 rotors) are characterized by battery power, vertical takeoff and landing (VTOL) capabilities, a small payload of a few kg and short ranges (e.g., 10 miles). See Figure 1 for an example from the partnership of Matternet and UPS. Similar drones are heavily used in imaging and sensing applications, as well as in some medical delivery applications, including with automated launch and landing facilities (e.g., [26]). Longer range drones are used in global healthcare applications (see Figure 2), where payloads of several kg and ranges of over 100 km are common. Unlike rotocopters, these drones rely of lifting surfaces like wings (to provide greater lift and thus require less energy necessary for longer flights), whether of a fixed wing, tilt-rotor, or hybrid design. Hybrid drones may have a collection of rotors in different orientations to allow VTOL capability as well as efficient forward flight. Figures 3 and 4 show recent (2019) examples of

FIGURE 2 Zipline fixed wing drone. Source: https://www.cnet.com/pictures/take-a-look-at-ziplines-new-drone-delivery-system/ [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 3 Amazon hybrid drone. Source: https://www.usatoday.com/story/money/2019/06/05/amazon-drone-delivery-shopping-giantunveils-new-prime-air-drone/1358260001/ [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 4 Google hybrid drone. Source: https://www.engadget.com/2019/04/09/alphabet-wing-drone-delivery-service-australia/ [Color figure can be viewed at wileyonlinelibrary.com]

hybrid drones from Amazon and Alphabet (Google). Heavy lift drones are also being developed by a number of companies with payloads measuring in hundreds of kg or much larger (e.g., [4]). This includes a growing number of drone taxis that may someday provide personal drone transport.

An important opportunity for practical impact and research challenges is the combination of drones with other vehicles, such as trucks or public transit. Having trucks that carry, launch, and recover drones (e.g., on the roof) allows the short range and small payload limitations of a drone to be overcome by restocking and recharging the drones at a truck. Further, the mobile capability of the truck as a drone base—and the ability of the truck to make deliveries in parallel with drones—provides new opportunities and potential efficiency gains (with Murray and Chu [29] being one of the earliest articles). These settings often lead to very challenging routing and scheduling issues as synchronization of the operations of multiple vehicles (e.g., trucks and drones) may be required. Other vehicles proposed for combinations with drones include public transit [9,21], blimps [5] and other aircraft ([27]). Earlier research with multiple vehicles working together in similar settings, but not aerial drones, may be instructive (e.g., [25])

3 | MODELING ISSUES

Although aerial drones fly in a three-dimensional space, they are typically modeled in the Operations Research and network literature as traveling on a network or in some cases in 2D space. (Ground drones naturally lend themselves to being modeled on a network as they use roadways or sidewalks, while subsurface sea drones operate more in a 3D world.) Certainly the freedom of travel for drones offers some interesting opportunities that do not apply to ground vehicles limited to road travel (although other aircraft may have similar freedom, but not at the low levels of altitude where drones are envisioned to operate).

Network-based research on drone routing problems uses a typical network with arcs representing travel between nodes that may represent launch and recovery locations (drone bases or fixed locations), delivery points, recharging locations, etc. Node routing models with drones typically use a network with a given discrete set of nodes, where an arc represents feasible travel by the drone between nodes. This allows the network to be defined by the drone's flight capabilities and relevant regulations and obstacles. Drone arc routing models are fundamentally different in that typically a network to be serviced (e.g., inspected) is provided, but the drone has the capability also to travel off the network, and may depart from, or arrive at, any point along any arc.

The actual flight paths of drones can be quite complex and will reflect the flight dynamics specific to the drone type. There is a considerable literature on path planning and trajectory optimization that includes flight dynamics (i.e., position, velocity, acceleration, forces, and moments) [13]. For example, the curving flight path of a fixed wing drone when it turns may follow a Dubins path [38], as instantaneous changes of direction at a node are not possible. Drone network routing research generally assumes a deterministic distance (or a deterministic time or cost) between two nodes, without a clear expression of how that is determined, as well as a fixed time or cost at a node for some activity (e.g., delivery, retrieval, recharge), without detailed modeling of what actually happens at the node, such as the energy consumed in various activities (hovering, landing, takeoff, recharging, etc.). Most models neglect the local logistics and scheduling for launching and recovering multiple drones from a node or a truck in a short period of time, though Murray and Raj [30] is a notable exception. Incorporating drone flight dynamics in a network model would require more detailed modeling at the nodes and arcs to account for different times or costs on how a vehicle actually travels (perhaps similar to detailed modeling of roadway intersections with turn lanes).

Given the wide range of potential application areas for drones, one can ask, "Are there existing network-based models that fit these areas—or are new models required?" To date, many drone network routing models have focused on extending TSP and VRP network models to handle drone travel or and truck-drone combinations. The many varieties of truck-drone combinations have been a particularly rich area of research as the synchronization issues of two vehicle types requires addressing both routing and scheduling decisions. Thus far, much of the focus has been on simple objectives to minimize the maximum time or cost related to routes.

Many drone applications also naturally lend themselves to location-routing problems due to the short range of drones, the inherent need for drones to be based at facilities (which may be mobile), and the use of drone recharging/refueling stations to extend the range of service for drones. Research in this area can certainly benefit from the rich research on location-routing problems and on electric vehicle routing.

We also note there is a lack of standard data sets reflecting real-world drones and drone operations. In many cases, the data used in drone route modeling have been derived from small- scale tests with small drones and are assumed to apply in larger-scale delivery settings. Because there are only few "production level" drone delivery systems currently in place (e.g., Zipline's blood delivery operations in Africa), there is not a good set of drone cost and performance data available to use in modeling. Yet, managerial conclusions drawn from models based on unrealistic drone types may be of limited value.

We believe future research should incorporate better modeling, more realistic drone types, and more drone applications. These new models will incorporate better representations of the constraints affecting the drone itself, as well as better representations of the unique features of new applications for drones. The home delivery drone industry appears to be ramping up, with major players (e.g., UPS and Amazon) moving beyond drone pilot tests and moving closer to regular on-going drone delivery operations in selected locations. In parallel, the successes from using drones in global healthcare has led to many tests in Africa and Asia, and further expansion seems likely.

In the following sections, we discuss six key areas for modeling drone routing and drone systems, with each introduced by a fundamental question.

3.1 | Are we accurately modeling the key drone capabilities correctly, for existing drones and those likely to be used in the future?

Key attributes of drones include range, payload, speed, energy consumption/battery life, package size and shape, and locations at which a drone could feasibly launch and land (or deliver). Some of these are determined by the design of the drone itself (and physics) and others are determined by the operations of the drone in particular environments (including weather, temperature, elevation, etc.). The first four of these attributes (range, payload, speed, and energy consumption/battery life) are critical and exist in a tradeoff as a longer range generally requires a smaller weight (or larger battery or fuel amount), and the range, payload, and speed all affect the battery life (or fuel use). The use of battery power for small drones used in many applications leads to a fairly small range. A critical issue related to battery life is to better understand the energy consumption for different drone types and different drone activities. Drones are very complex aircraft moving in three dimensions subject to the forces of lift and drag, all of which vary considerably with the drone design, size, and operation. The role of speed in drone models is another important issue, as many traditional vehicle routing models ignore vehicle speed (or assume a constant speed), while drone speed strongly influences the drone travel and energy consumption, which significantly impacts battery life and drone range. Speed is especially important as that impacts both cost and service (e.g., revenue or health outcomes) directly. Hovering is a feature of drones without an exact counterpart in ground vehicles, as hovering requires considerable energy (that can be similar to that required for level flight). Properly modeling drone energy consumption is critical to better understand both cost and environmental impacts of drone use, and energy consumption is influenced strongly by the design of the drone, the payload, and how the drone is operated, including speed. We are encouraged by recent research that incorporates more comprehensive modeling of drone operations, such as Kirchstein [24] and Murray and Raj [30].

Existing drone research has used a variety of different models for drone performance, often based on smaller drones, and in some cases with field measurements. Some studies (e.g., [37,43]) have provided more comprehensive and forward-looking models for drone delivery. We note that some drone delivery models include a large number of parameters (to calibrate), whose values may be highly uncertain or variable from one drone to another. With the advent of wider-scale drone delivery moving beyond the pilot testing phase, we hope that accurate data will soon be available from the actual drones to be used for delivery systems. Recent data from short range rotocopter delivery drone tests [17] and field experience in Africa with seven longer range drone types [42] may be useful.

We encourage researchers to make it a priority to integrate new more accurate real-world data into their modeling. Until then, models should be tested across a wide range of plausible parameters (e.g., see [18,44]).

3.2 | Are we accurately modeling the important constraints correctly?

Key constraints for drone operations include regulations, issues of privacy and public concerns, and spatial and temporal restrictions. The regulatory issues surrounding drone use remain a challenge in many locations, although good progress in being made in places where the value of drone delivery has been demonstrated. This includes many of the global healthcare applications in Africa and is due in part to the substantial efforts of healthcare-oriented NGOs (such as UNICEF and the Bill and Melinda Gates Foundation) and governments (e.g., USAID). The privacy issue from drone overflights remains a concern for some, although good progress has been made from education campaigns and the advantages of drones (fast delivery) may well overcome resistance among much of the population. Additional regulations and policies restricting the human viewership of images collected by drones may also help ease concerns.

Incorporating spatial constraints (e.g., no fly zones) and temporal constraints (no flights at certain times) is an important issue to create more realistic models. Certain areas (e.g., airports and some government and critical facilities) will likely remain off-limits to drone fly-over, so optimal routes need to incorporate those restrictions. (See [20] for one example.) Another issue that may be relevant for drones involves areas subject to communication interference or interruptions, as in congested urban regions, where a drone may have restricted (or no) communication to and from other drones or fixed locations. However, existing research on routing and location problems with barriers and restricted areas provides a ready source of inspiration for drone models.

Additionally, it is important to incorporate constraints that respect “local logistics” at the depot and at launch or retrieval/landing sites. Local logistics include deconflicting multiple launches/retrievals at the same location (including scheduling a sequence of launches/retrievals and with consideration of drone energy consumption as for hovering while waiting in a queue; (e.g., see [30]), incorporating time required to swap a battery or get launch approval, accounting for the time it takes to load/unload a package from a drone, etc.

Thus far, there has been little research on drone routing related to Unmanned Aircraft System Traffic Management (UTM) and the constraints UTMs may impose. Though this may reflect the uncertainty surrounding governmental actions with respect to new technology, we believe moving forward, there will be increased understanding of UTM requirements, and future model constraints should reflect these. The possible establishment of drone corridors or waypoints for drone traffic necessarily has an impact of drone routing. While there is much research on air traffic management systems for passenger aircraft, how much of that carries over to drones is unclear.

3.3 | Are we focusing on the right objective function?

Most existing drone routing models have addressed straightforward objectives based on time, distance, or travel cost, often extended from other vehicle routing models. However, many different objectives have been used depending on the perspective of the modeler and the application. Time based objectives include minimizing the total delivery time for a set of packages, minimizing the time of the last delivery, minimizing the time until all vehicles, including drones, return to the depot, minimizing the time to cover (fly over) a set of edges, minimizing the time to reach a set of critically ill people, etc. Economic (usually cost) based objectives may include minimizing the cost for the distance traveled by drones (or different types of vehicles) to complete a set of deliveries, minimizing the total cost including fixed costs for vehicles and travel costs to complete a set of deliveries, minimizing the cost to service a set of arcs, maximizing the value of the activities (e.g., deliveries or missions) completed, etc. Models addressing profit are rare, though Baloch and Gzara [2] is a notable exception. Some research has also addressed environmental objectives with battery powered drones by converting from travel distance to energy consumption (based on the drone energy consumption per km) and then to emissions (based on emissions per unit of energy). This requires appropriate consideration of the source of the energy (electricity generation) and should include a life cycle modeling approach as well (e.g., see [15,37]).

While drones may often be viewed as simply a new transport mode in an existing market (e.g., home delivery), perhaps there are different objectives that should be employed for drone operations. A key issue for many transport systems, especially passenger travel, has always been safety. So an important questions is "how should safety be modeled for drone systems?". This requires identifying who or what is affected by unsafe drones or drone operations and what are the likely impacts. A high profile and well-publicized accident involving nascent technologies may produce a disproportionate backlash among the public. Reliability issues for drones play a role in this topic as well. If, for example, a relatively high percentage of drone operations cannot be completed due to some circumstance, what are the operational costs and costs associated with dissatisfied customers? Are there factors (e.g., weather) that have a more severe and systematic impact on drone operations relative to traditional alternatives? Certainly, winds and weather have a larger impact on small drones than on trucks. Additionally, there may be costs associated with training drone operators, repair technicians, and educating the public about safely receiving service from a drone. Customers may have preferences for the delivery location and delivery mode for their packages. Moreover, package delivery by drone may require the customer to be present to ensure the package was delivered successfully and moved to a secure area. How can we incorporate customer preferences into the objective function?

When rapid drone delivery becomes widespread, drone airspace may become congested, particularly in densely packed neighborhoods or near drone facilities. This may increase collision risks and require drones to slow down. Incorporating airspace congestion into objective functions may be useful. If each drone launch and landing is controlled by a centralized authority (e.g., the FAA), then the centralized authority may consider a variety of objectives, including minimizing the average (or maximum) launch delay, minimizing the average (or maximum) arrival delay, maximizing fairness of delays across various drone operators, and minimizing deviations from preferred flight plans and trajectories. Given that drones operate at a much lower altitude than passenger aircraft, are the interactions with people on the ground (e.g., noise) an issue that needs to be modeled, as a component of the objective function? There are many similar questions that require careful analysis in forming a useful objective for drone routing research. Moving forward, we also suggest, as much as possible, formulating objectives that drive operational decisions, rather than starting with artificially imposed decisions as constraints. For example, an assumption in much of the literature is that only a single (small) drone is launched from a truck at a stop, or that multiple drones can be launched and recovered simultaneously. Better models (e.g., [30]) allow multiple launches per stop and carefully model the extra costs and benefits, such as the time required to deconflict the launches/retrievals of multiple drones. We encourage modelers to use the objective function to drive decisions such as how many drones to use, and how to use them, rather than adopting assumptions that are not always well founded. Though more complex and generalized models are usually more difficult to solve to (near) optimality, the increased flexibility may result in significant benefits relative to more restrictive, though simpler, models.

3.4 | Based on the above, are we utilizing the best model of delivery using drones?

Many papers in drone research thus far have focused on home delivery settings (warehouse-to-consumer) using a drone-only model or truck-drone coordination models with a homogeneous fleet of drones (and trucks). Are there other models that may prove more fruitful? Does having drones deliver to secure locker locations (e.g., Amazon Locker), rather than individual homes, simplify operations in practice? How does the use of recharging platforms impact the optimal mix of drones required? Since different drones have very different performance characteristics, optimal routing for a heterogeneous fleet of drones provides an interesting opportunity (see, e.g., [8,40]), though mixed fleets add operational and computational complexity. Are there other "outside of the box" models that work even better? In what conditions (rural delivery, urban delivery, global health applications, etc.) does each model prove superior?

We believe an often-overlooked portion of the model is the "last meter" of delivery. Drones may make deliveries by several different modes, including landing and releasing a package, using a tether to lower a package to the ground, or parachuting a package. There are some safety advantages from the parachute and tether mode by keeping the physical separation between the drone and things or people on the ground, but the landing mode provides a more accurate placement of the package, and allows a non-empty backhaul trip. Each mode has its advantages and disadvantages, and each mode affects the routing due to different time and energy requirements. Moreover, the last meter delivery mechanism greatly affects the set of locations where delivery can feasibly be performed, and can strongly impact the customer experience. Likewise, depending on the mode of delivery and level of required interaction from the customer, routing decisions may be greatly impacted by customer actions at the point of delivery.

3.5 | What methodological changes and advances are required to solve these problems?

As the capabilities, constraints, objective functions, and routing models for drones may differ in substantive ways from traditional vehicle routing problems, the development of algorithms and solution techniques that are well-equipped to optimize drone routes and drone delivery systems are necessary. These present some new challenges. For example, there are several truck-drone problems where the drone must synchronize with other vehicles or workers. Although some papers have constructed exact or heuristic algorithms that incorporate synchronicity constraints, finding optimal solutions for large-scale problems with synchronization remains elusive. In typical VRPs, the person driving the vehicle is a service provider (e.g., making a delivery) with the vehicle often carrying some item(s) used in the service (e.g., food, parts, or medical equipment); thus the person and vehicle travel together. Drones (and other autonomous vehicles) allow the separation of the transport of the human service provider from the item travel via drone. In many cases, the item can travel separately by drone without the service provider (person) involved, as long as the customer is there to receive it or a "drone box" is available for safe delivery and storage. For other situations, the person is needed at the customer site along with some item(s), to receive the items and provide the service (repair, taking blood, vaccination, etc.). However, separating the person travel and item travel may allow better routes as, for example, when the drone can replenish the service provider with perishable products or with items that are requested only once the service provider is with the customer (e.g., healthcare items). This type of setting requires complex synchronization of multiple routes, so modeling is a challenge.

Because drones are not constrained to operate on a street network with fixed speed limits, developing solution methods that treat drone speed as variable would deviate from much of the vehicle routing literature. Although some routing literature explicitly considers flight dynamics and nonlinear energy consumption models (e.g., [30,37]), there may exist opportunities to modify or fine-tune this in specific contexts. With the emergence of FAA rules restricting the altitude for commercial drone flights, perhaps there exist special network representations that can take advantage of this geometry, or future legal drone airspace geometries.

Drones may be more sensitive to unexpected occurrences during delivery than traditional vehicles. For example, strong winds or a customer who does not show up to receive their package on time may force a drone to expend more energy than originally planned (e.g., carrying the package back to the warehouse or a safe location) (for the impact of winds, see [24]). In drone routing problems involving coordination with trucks or other vehicles, traffic or other factors may delay the rendezvous between a drone and/or other vehicle. Even in the case of a fixed drone launching location, an absent employee or a mechanical failure of another drone may necessitate landing at another location. Future drone routing solutions may need to incorporate the enhanced role of stochastic elements and the capability for recourse and recovery mid-route.

Because the world of drones is changing so rapidly, solution methods that contain added flexibility to accommodate a range of assumptions, input parameters and constraints could be especially valuable for the variety of applications that may arise. Combinations of existing drone models may also have utility in the future. However, increased generalizability often yields computationally more difficult optimization problems. To that end, solution mechanisms that contain elements of modularity/separability may have greater staying power due to increased flexibility and, at times, scalability. Several papers (e.g., [1]) contain formulations that use, as an input, the set of feasible actions (called "operations"). Because the solution method is essentially agnostic to how the cost and/or feasibility of each operation was determined, it is possible to add custom logic, reflecting various regulatory or logistical considerations that impact cost and feasibility without requiring a change in the core solution method. Integrating more realistic nonlinear energy expenditure models (see, e.g., [44]) can aid in better modeling of problems.

Solution mechanisms that are able to accept arbitrary energy expenditure models or exploit certain dynamics common in many energy models (e.g., convexity of energy expenditure function) are likely to be more useful.

Finally, it is worth noting that there exists a fundamental question of how we should represent feasible regions for drone operations. Should we use continuous models and variables, or discrete variables and network-based models to represent drone flight paths? Thus far, there has been some work on both fronts [29,34], but further work is needed to better understand the capabilities and limitations of each approach.

3.6 | WHAT NEW APPLICATIONS MAY ARISE FROM THE USE OF DRONES?

Some drone applications carry over in a straightforward way from traditional aircraft. This includes using larger drones to deliver goods over a moderate/longer distance and obtaining imagery over a region. However, there exist many new applications that have already been developed for drones, and there likely exist a myriad of other applications that have not yet been developed or have not yet received widespread recognition. The applications that will emerge will naturally exploit unique characteristics of drones. These characteristics include:

- The ability to move in 3-dimensional space, and thus avoid obstacles on the ground.
- The small size relative to traditional aircraft.
- The ability to exploit the Euclidean distance metric (subject to airspace restrictions).
- The high speed of drones relative to traditional delivery vehicles (e.g., trucks).
- The unique ability to establish a line-of-sight in some scenarios.
- Autonomy.
- Lower construction/acquisition costs relative to traditional vehicles.
- Possibly lower energy usage and cleaner energy sources relative to traditional vehicles.
- Reduction of street traffic congestion.
- Potentially better signal quality with satellites, other drones, etc. over some regions.

Many interesting questions arise from these characteristics: Does the speed of drones in an urban environment facilitate rapid delivery of goods that were previously not viewed as suitable for delivery (e.g., certain perishable goods or urgent care items, etc.)? Will drones facilitate new means of communication that were previously not possible? Can aerial and ground-based drones, and automated vehicles and warehouses, work in concert to facilitate fully automated delivery? Can drones be integrated into public transport systems efficiently (e.g., Huang et al. 2020; [9])? Can the efficiency of service workers be increased by drones delivering necessary parts or medical supplies on an as-needed basis, rather than having the worker return to a centralized location? Is it possible to rapidly rebalance inventory between multiple warehouses, especially in the context of next-day or same-day delivery requirements using drones? What location-routing models are needed for drone services? Are there new inventory-routing models with drones? Can drone taxis provide new services for rapid urban transport or large-scale commuting? What new opportunities would be created by very heavy lift drones (e.g., with 10 000 kg payloads)? Might heavy lift drones be used for loading and unloading containers on ships, replacing or expanding the capacity from shore-based cranes by using both sides of a ship for loading? How best might multipurpose drones be used for imaging, delivery and pickup on a single trip? How can a collection of such multipurpose drone trips be designed to serve a set of delivery customers while mapping a region during the travel to and from the deliveries (e.g., [22])? Are there opportunities for teams of drones to work together, for example, with one drone identifying an infrastructure problem through inspection, and then a second drone called in to repair the problem autonomously? With the miniaturization of drones, could swarms of many coordinated, small drones lead to new applications, and new routing problems? (Already swarms of drones are used in entertainment and communications applications.)

The sudden emergence of the COVID-19 pandemic has motivated investigation of many potential uses of drones [41]. These include (*a*) delivery of goods (e.g., personal protective equipment or food) to socially isolated individuals or medical workers, (*b*) spraying of streets or other surfaces with disinfectant or water, (*c*) enforcement of lockdown and/or curfews, (*d*) monitoring of macro-level flows of people or individuals toward contact tracing and epidemiological modeling, (*e*) body temperature scanning of people, (*f*) conveying information via carried visual signage or through flying broadcasts, (*g*) maintaining security patrols at various facilities that have significantly reduced onsite staffing, and (*h*) inspecting critical communication, energy, or transportation infrastructure that was previously inspected in person. Of course, each of these ideas must be more efficient than existing solutions and may raise other issues (e.g., privacy, safety).

4 | FINAL THOUGHTS

There exists great promise in the development and expansion of drone routing applications, and with this great promise comes great uncertainty. Although it is impossible to project with certainty what uses of drones will arrive in the future, or the performance characteristics and costs of future successful drones, we have identified six key areas where we believe advances in drone research may occur in the coming years in the operations research/network optimization literature. In addition, we ask many questions that we believe may be fruitful for the research community to answer in the coming years. Despite the separation of ideas into six areas for the sake of exposition, these areas are certainly not disjoint, and are in fact highly interdependent.

This is an exciting research area and we offer some broad summary suggestions for future research here. First, models should consider more details to better represent relevant aspects of the drone service provided (e.g., delivery, or surveillance), including the business objectives (e.g., cost), any operations with multiple drones, and any scheduling and coordination issues with other vehicles (including drones). Second, models should better reflect the drone range constraints, especially the fundamental range limits (time and/or distance) based on realistic energy modeling, and realistic flight profiles that include the vertical component and likely hovering. Third, models and solution methods should be developed to handle more of the stochastic aspects of drone operations (e.g., travel times, delivery times, etc.), especially due to weather conditions. Fourth, there should be more field testing of drones similar to those likely to be used in actual operations (e.g., for large-scale drone delivery) and with realistic flight profiles (which depend on the environment, regulation, UTM, etc.). Fifth, given the current uncertainty about future drone designs and operations, and the corresponding lack of accurate data for particular settings, researchers should perform a sensitivity analysis with a very wide range of values (e.g., drone energy consumption rates) to ensure the robustness of their findings.

With the rapid growth in academic interest in drone operations, there is potential to accelerate drone applications if academics, regulatory bodies, and the private sector share information and ideas. We especially hope to see drone routing research motivated by actual or proposed real-world drone applications in the public and private sector, so that the research can have greater impact. We also hope to see more drone research that might inform policy (especially drone regulations), improve practice, impact people positively (e.g., with a positive impact on environmental and social systems) and advance theory. We encourage, in particular, the formation of a subgroup (e.g., within an INFORMS or Euro subgroup) that could coordinate OR approaches to drone problems, ideally by hosting interdisciplinary international meetings that include researchers from engineering, policy, drone companies, etc. Additionally, the creation of realistic standardized datasets may be extremely useful to researchers and practitioners alike to test future drone routing models, solutions, and algorithms. This includes a database of measured, reliable drone parameters (e.g., speed/energy consumption profiles, battery capacity, package carrying capabilities, costs, emissions, etc.) that accurately reflect the drones used in various settings. Standard sets of test instances, ideally based on real applications and customer locations, will facilitate comparison between future models and help advance research.

The use of drones and other new technologies presents both unique challenges and opportunities. Although the volume of research about drones in the operations research community has rapidly expanded in recent years, we believe that this is only the start. Once the use of drones becomes widespread, possibly in ways not envisioned today, we believe the importance of drone research on routing, as well as on broader drone ecosystems, will only increase, and many new questions will emerge for the operations research community to solve.

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