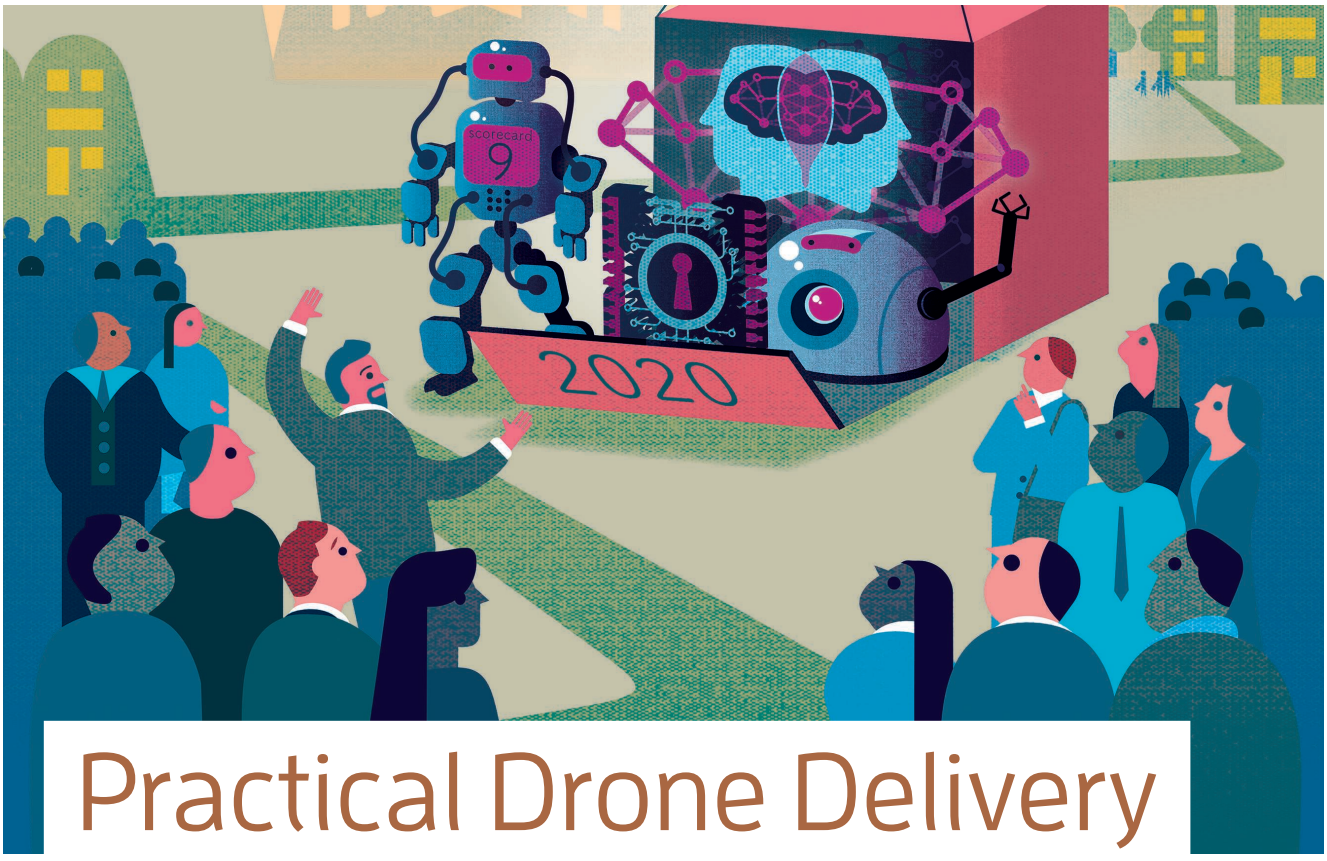

Practical Drone Delivery

Eitan Frachtenberg, Reed College

Despite its enormous economic impact, the parcel delivery industry has evolved slowly over the decades with the biggest innovations coming from GPS and planning algorithms. New developments in the technologies of drone delivery, such as aircraft design, battery improvements, and control software, could transform this industry and, consequently, society as a whole.

Parcel delivery generates revenues of more than US$200 billion per year in the United States alone.[1] Small-parcel drone delivery will grow rapidly in the near future and replace a significant portion of deliveries in person. If successful, it could soon be followed by drone delivery of more critical, time-sensitive, or larger payloads.

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IMPACT

In recent years, there have been significant advances in a variety of technologies designed to deliver cargo by drone, primarily driven by industrial efforts. These drones may be aerial, marine, or terrestrial. Some are fully controlled by a remote human operator, while others are fully or partially autonomous. Drones range in parcel size, from a few kilograms to container ships. In this article, we focus on arguably the most disruptive of these models: small-parcel delivery by autonomous or semiautonomous drones and, in particular, by aerial drones.

A successful deployment of delivery drones at scale could radically transform the industry, replacing thousands of drivers, fossil fuel-powered delivery trucks, road traffic, and centralized delivery hubs with drone operators, small aircraft, air traffic, mobile hubs, and point-to-point delivery. This broad transformation could result in reduced congestion in existing road infrastructure, increased road safety, and improved accessibility to areas with poor road infrastructure.[2] In addition, numerous other applications could be improved, expanded, or created. The following sections detail the main applications under consideration.

Merchandise delivery

Merchandise delivery, one of the best-known use cases for drone delivery, has the potential to significantly reduce the cost and carbon footprint of this enormous industry.[3] For example, as of this writing, Google is experimenting with drone delivery in Australia. Amazon, with the U.S. Federal Aviation Administration's (FAA's) limited blessing, expects to begin actual aerial drone deliveries in the United States within months and is also experimenting with terrestrial delivery robots. Walmart is expected to overcome the drones' current constrained range with their extensive network of retail locations that can reach nearly 90% of Americans.[4]

Courier delivery

Similarly, courier delivery could take advantage of the same technology but with a different traffic model. Instead of the hub model of merchandise delivery (warehouse to consumers), courier delivery requires point-to-point travel between two private parties.[5] Depending on the dispatch model for courier drones, this distributed traffic pattern could either alleviate or exacerbate their range limitations, presenting a different set of technical challenges and solutions compared to merchandise delivery.

Food delivery

Another industry particularly well suited for drone delivery due to the time sensitivity of its perishable cargo is food delivery.[6] This large market, estimated to grow globally to more than US$160 billion by 2023,[7] is currently attracting numerous proof-of-concept prototypes, both terrestrial and aerial. In the United States alone, trials are underway in cities, including Washington, D.C. (by Starship Technologies), Los Angeles (by Postmates), San Diego, California (by Uber), and Phoenix, Arizona and Houston, Texas (both by Nuro). Similarly, perishable floral goods could enjoy the same benefits from timely drone delivery.

Humanitarian aid

Humanitarian aid, that is, providing essential supplies to otherwise inaccessible people in war or disaster areas,[8] is another useful application of delivery drones. Similarly, medical delivery of organs and blood is another time-critical, life-saving application that has previously seen field trials.[2,9]

Passenger delivery

Perhaps the most ambitious of all applications and, therefore, the farthest into the future, is passenger delivery by drone. Various companies, for instance, Uber, with its Elevate project, are collaborating with aviation companies, such as Pipistrel, to develop autonomous, short-range, passenger-carrying drones.[10]

TECHNOLOGY CHALLENGES

Several critical challenges remain before the full realization of the promise of delivery drones can be achieved. These as-of-yet unsolved challenges represent an active area of study and regulation, and the successful deployment of delivery drones depends on the development of practical solutions. These challenges can be broadly divided into three categories and one shared prerequisite technology.

Capability

Compared to standard delivery by truck, the two principal limitations of delivery drones, especially aerial drones, are range and payload. The necessarily lightweight batteries on aerial drones cannot provide enough power for long-range or heavy payloads. For instance, Amazon's current prototype can deliver packages of up to 5 lb for a distance of 15 mi. Because not every destination is within 15 mi of a warehouse, each dwelling is not an accessible house, and not all packages weigh fewer than 5 lbs, the first wave of commercial delivery drones can only augment current delivery methods, rather than fully replace them. Drones, for example, could initially be used to bring packages closer to the recipients in smaller centralized distribution centers, rather than to their doorstep. Or, conversely, they could be launched from delivery trucks as a hybrid solution to solve the "last-mile problem." This final step is the most expensive and time-consuming part of delivery by truck, especially in areas of congested or underdeveloped road infrastructure.[6,11] Improvements in battery and drone technologies will likely expand this envelope only incrementally in the near future, although these increments may suffice to replace a significant fraction of truck deliveries.

Other capability challenges relate primarily to navigation: how to reach a

precise destination (the "last-centimeter problem"[5]); ensuring safety to people and property, whose location may be mapped in advance or be unexpected;[11] planning the logistics of a drone-only or combined truck/drone fleet;[12,13] and overcoming and planning around mobility challenges and obstacles, for instance, stairs, uneven terrain, debris, and so on. Planning and navigation, especially autonomous navigation, is an open research area. Driven, in part, by the commercialization of autonomous vehicles (see "Cognitive Robotics" in this issue of *Computer*), significant progress has been made in recent years. Yet despite these new developments, the technological challenges are still by no means solved. Further evolvement may also require, or at least benefit from, continued advances in drone-borne sensors, such as cameras and radar, as well as real-time computation to interpret the sensor data.

Efficiency

The efficiency of delivery drones, in terms of time, cost, and energy, is directly related to their economic viability and environmental footprint. For example, it is not always clear that the net carbon emissions of delivery by drone are necessarily lower than those of delivery by truck[3,14] or that drone delivery cost is necessarily economical.[15] Improving the efficiency of drones by making them faster, cheaper, greener, quieter, and able to handle more traffic are all engineering challenges with a direct bearing on the success and sustainability of the drone-delivery concept.

Coordination

When we think of coordination, perhaps the first picture that comes to mind is a science-fiction vision of a sky crowded with drones and airplanes, zooming by each other in a tightly choreographed dance of near misses and shifting routes. In reality, a combination of technical limitations and cautious regulation will likely keep the skies mostly wide open for years to come, with strict separation between aircraft. The FAA, as an example, has mandated that all piloted aircraft in certain busy airspaces are required to use a particular technology called the *Automatic Dependent Surveillance-Broadcast* (*ADS-B*), starting on 1 January 2020. ADS-B allows for all participating aircraft and controllers to know the location, altitude, and velocities of nearby aircraft as an additional tool to the existing traffic management models of centralized radar and "see and avoid." Technically, the FAA requirement is for only ADS-B out transponders, specifically, for each aircraft to transmit its own position; however, many aircraft are also equipped with ADS-B in receivers, allowing them to visualize the relative positions and velocities of other participating aircraft. Similar to several other drone manufacturers, DJI now equips its drones with ADS-B transceivers so that they can broadcast to or "see" (and sense and avoid with the proper control or software) other aircraft in the vicinity.[16]

Coordination also happens centrally because delivery trips must be scheduled and planned to reduce congestion, delivery times, downtime (for charging), cost, and global effects of localized delays. Planning and scheduling at this scale is a notoriously difficult computational challenge,[12] where mistakes can sometimes be highly disruptive, as evidenced by cascading airline delays. To develop this technology, NASA has launched its Unmanned Aircraft Systems Traffic Management project in anticipation of ubiquitous delivery by drone.[6] Several private companies, like Flytrex, are also experimenting in this space.

Another important aspect of coordination is the legality of deliveries. The delivery of contraband is already a challenge for existing delivery technologies. But the removal of the human element and the potential increase in delivery scale with drones could exacerbate the problem and require novel technological approaches to mitigate it.

Artificial Intelligence at Edge

An overarching technological challenge that affects all three previously mentioned categories is the control hardware and software running on each one of these drones. This so-called AI at Edge challenge is both a prerequisite and a beneficiary of the development of delivery drones. The autonomy of drones requires the acquisition and interpretation of sensor data with tight time and energy constraints. Some of the computational tasks involved include image processing and recognition, risk assessment, route planning under constraints, and physics computations.

RISKS TO PREDICTION

As discussed in the previous section, a number of technological challenges exist that could derail, or at least delay, realizing the full potential of delivery drones. And like all technological predictions, one ever-present risk is simply that the required technologies will not be developed quickly enough, thus delaying their full implementation. Additionally, there are a few other risks that could stand in the way of this realization, which relate more to people than to technology.

Primary among these risks is regulation, including federal, state, and

local.[17] The airspace above a nation, similar to the radio-frequency (RF) spectrum, is regarded as a limited national resource with concrete economic and security implications and, as such, is tightly regulated. Incidentally, most drones rely on radio communication, which itself is subject to regulation as part of the RF spectrum. In the United States, drone regulation began in 2005 with the FAA's Unmanned Aircraft Systems Policy 05-01, which delineates guidelines for drone operators. Commercial drones were banned in 2012, but approval restarted on a case-by-case basis in August of 2013. The regulations for commercial and recreational drones have evolved and continue to do so. The operators of commercial drones must still meet certain licensing, operation, and registration requirements to enhance safety and security in the increasingly crowded national airspace.

The FAA has launched and recently expanded its Low Altitude Authorization and Notification Capability testing program, which allows operators to coordinate the use of drones near approximately 600 airports utilizing a dedicated website. Some cities and states impose their own additional restrictions, although the legality of these has been challenged by individuals and the FAA. Nevertheless, the regulation process continues to evolve and slowly lift restrictions on drone payload, range, and airspace use, concomitant with the technological developments that enable these improvements. On the terrestrial side, which is typically subject to less federal jurisdiction, regulation has progressed at varying rates, with some states already permitting or experimenting with delivery drones. Virginia and Idaho became the first two states to pass a law allowing the use of sidewalks for autonomous ground-based delivery drones.

Among the reasons for regulation, perhaps none are more prominent than safety and security. Drones are vehicles and, as such, are subject to vehicular accidents, whether due to operator mistake or technical faults. Thus far, there have been relatively few attention-grabbing accidents/incidents related to drones, possibly due to conservative regulation. However, as technology evolves and whenever humans are involved, the occasional safety mishap is inevitable. Even a single, high-profile accident with significant casualties or, worse yet, a malicious attack or security hack involving drones could completely alter public perception and, consequently, social acceptance of drones. It is therefore imperative for large players in the drone market, as they work to ease regulation and increase adoption, to assuage public fears about the risks involved, or they could lose the fight on the public relations front.

Another motivation for regulation, and an important factor for social acceptance, is the concern for privacy. Drones can be used to violate individuals' privacy, even when used for unrelated purposes, notably, package delivery.[18] Several states have specific laws in place to protect people from privacy invasion by other individuals using drones, but it is still unclear what regulations would look like in a future with ubiquitous commercial drones. For instance, how would regulation handle the occasional, but probably commonplace, accidental violation of privacy as drones fly over individuals' property? How would individuals' privacy be protected from use and abuse of commercial drones by private companies or law enforcement? Comparable to safety and security, the utility of commercial drones must be carefully balanced against individuals' rights and expectations if the technology is to achieve acceptable, widescale adoption.

Even if safety, security, and privacy are reasonably assured and permissive regulation allows for the growth of delivery applications, it still may be human resistance that slows or blocks this growth.[19] One example of resistance is the theft or vandalism of drones, which could eliminate the economic viability of the technology. Another form of resistance is political, for example, in objection to drones' noise pollution, effects on wildlife, or aesthetic impact. Similarly, drone adoption could face political and market pressure from displaced commercial operators (for instance, truck-based delivery companies), not unlike the pressures experienced by electric vehicle manufacturers from some of the traditional motor companies. For the time being, however, it appears that some of these companies, such as UPS and DHL, are at the forefront of drone research.

Drones are poised to take over the delivery world. Compared to human drivers, terrestrial drones can travel at favorable costs, and aerial drones can bypass the complex urban navigation challenges altogether at favorable speeds. This disruptive technology could scale a labor- and energy-intensive everyday task with game-changing efficiency. There are still important limitations to widespread adoption, however, based on technological and human factors. But if current trends continue, these limitations will quickly be overcome so that delivery drones may become practical as early as 2020 and ubiquitous in some areas shortly thereafter.

ABOUT THE AUTHOR

EITAN FRACHTENBERG is a visiting associate professor of computer science at Reed College. His research interests include computer systems, data science, and data compression. Frachtenberg received a Ph.D. from the Hebrew University in Jerusalem. He also received a remote pilot certificate (commercial drone operator) from the FAA. He is a Senior Member of the IEEE. Contact him at eitan@reed.edu.

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