



IoT Techniques and Elements for Drone Package Delivery Networks

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CONTENTS

- 1 Overview 4**
 - 1.1 Introduction 4
 - 1.2 Purpose..... 4
 - 1.3 Scope 4
 - 1.4 Structure 4

- 2 Motivations and Challenges 5**
 - 2.1 Delivery Speed 5
 - 2.2 Traffic Congestion..... 5
 - 2.3 Environmental Considerations / Carbon Footprint..... 6
 - 2.4 Labor Content 6
 - 2.5 Cargo Security 6
 - 2.6 Scalability..... 6
 - 2.7 Regulation..... 7
 - 2.8 Cost 7

- 3 Drone Delivery Networks 7**

- 4 Use Cases 8**
 - 4.1 Medical Cargo / Lab Samples 8
 - 4.2 Food Delivery 9
 - 4.3 Military Logistics 9

- 5 Drone Cargo Delivery Network Elements 9**
 - 5.1 Cargo Drones..... 9**
 - 5.1.1 Rotors (Propellers + Motors) 10
 - 5.1.2 Batteries..... 11
 - 5.1.3 Flight Control Computer 11
 - 5.1.4 Auxiliary Computers 12
 - 5.1.5 Network Connections 13
 - 5.1.6 Airframe 13
 - 5.1.7 Cargo Management System 13
 - 5.2 Landing Pads, Drone Docks Smart Drone Mailboxes and Automated Warehouses 14**
 - 5.2.1 Passive Landing Pads 14
 - 5.2.2 Drone Docks..... 14
 - 5.2.3 Smart Drone Mailboxes 15
 - 5.2.4 Drone-enabled Warehouses..... 15
 - 5.2.5 Sensors and Actuators 16
 - 5.3 Other Ground Support Resources..... 17**
 - 5.3.1 Wireless Network Nodes 17
 - 5.3.2 Sensor Arrays 17
 - 5.3.3 Security Screening Devices 18
 - 5.4 Control / Computing Resources..... 18**
 - 5.4.1 Ground Support Processors..... 19
 - 5.4.2 Edge Computing 19
 - 5.4.3 Cloud Computing 19
 - 5.5 Cargo Delivery Flow 20**

IoT Techniques and Elements for Drone Package Delivery Networks

6	Conclusions.....	21
7	References	21
8	Acknowledgements.....	24

FIGURES

Figure 3-1:	Drone Cargo Delivery Network Components.....	8
Figure 5-1	Elements of a Typical Cargo Drone.....	10
Figure 5-2	: Cargo Delivery Flow.....	21

TABLES

Table 2-1:	Large US Delivery Truck Fleets.....	5
Table 5-1:	Categories of Drones.....	10

1 OVERVIEW

This paper describes architectures for drone cargo delivery networks, and the IoT systems that support them. It starts with some motivations and challenges. Then, it describes an end-to-end drone cargo delivery network, use cases, and the elements that make it up. Next, the paper details specific elements of the network, with special emphasis on how IoT techniques, sensors and actuators are used in each element. An end-to-end flowchart summarizes the overall operation. Conclusions are offered.

1.1 INTRODUCTION

Drone-based logistics and delivery are an important emerging trend in both Business-to-Business (B2B) and Business-to-Consumer (B2C) supply chains. Drones (also called Uncrewed Aerial Vehicles or UAVs) can address many of the challenges in supply chains / logistics networks, replacing conventional truck-based logistics with faster, more efficient, more environmentally friendly alternatives. They are heavily dependent upon IoT technologies, including sensors, actuators, communication networks and intelligence at multiple layers to provide efficient, trustworthy autonomous operation. By one estimate, drone-based package delivery networks could eventually manage about 70% of urban parcel deliveries [1]. Many leading logistics companies have made investments in drone delivery technologies [2]. There is also significant research ongoing in drone delivery technologies, as shown in this literature review [3].

This paper will describe architectures for drone-based delivery systems and discuss how IoT techniques enable their efficient operation.

1.2 PURPOSE

The primary goal of this document is to educate readers about the important role of IoT sensors, actuators, interconnect and compute resources in drone delivery networks, and describe their advantages in advanced logistics systems.

1.3 SCOPE

The scope is a generalized drone delivery scenario, although the examples and network element descriptions used are centered on the class of drone typically used for residential delivery of packages weighing less than 10 kg, and the ground support infrastructures they use.

1.4 STRUCTURE

This document will be most useful to system architects, implementers, users, and regulators of drone delivery networks and services. It is organized as follows:

- Chapter 2 – Motivations and Challenges
- Chapter 3 – Drone Delivery Networks

- Chapter 4 – Use Cases
- Chapter 5 – Drone Cargo Delivery Network Elements
- Chapter 6 – Conclusions
- Chapter 7 – References
- Chapter 8 - Acknowledgements

2 MOTIVATIONS AND CHALLENGES

There are many reasons to implement a drone-based cargo delivery network, including desired improvements in speed of deliveries, traffic congestion, carbon footprint, labor content and cargo security. There are also many challenges to widespread deployment, including network scalability, regulation and cost.

2.1 DELIVERY SPEED

B2B and B2C customers require faster deliveries, trending toward the interval between the on-line order of goods and their delivery at the customer’s location being measured in hours or minutes. This challenge is especially acute for time critical or perishable cargo like medical supplies, biological samples, critical repair parts, or hot/cold/frozen foodstuffs. Traditional truck-based logistics networks cannot meet this challenge at scale. But drone-based networks can greatly improve last-mile cargo delivery delays for many classes of cargo.

2.2 TRAFFIC CONGESTION

Reduced traffic congestion is another motivator for drone delivery networks. According to the American Trucking Associations, there were 38.9 million trucks registered in the US and used for business purposes (excluding government and farm) in 2020 [4]. These add significantly to the traffic congestion, especially in dense city centers where delivery vehicles are often double-parked. Congestion due to delivery vehicles is expected to increase. Table 2-1 illustrates the sizes reported by the four largest truck delivery fleets operating in the US.

Delivery Fleets		
Service	Number of Trucks	Electrification Plans
US Postal Service	232,000	✓
UPS	126,000	✓
FedEx	86,000	✓
Amazon	70,000	✓

Table 2-1: Large US delivery truck fleets.

2.3 ENVIRONMENTAL CONSIDERATIONS / CARBON FOOTPRINT

Reduced carbon footprint for logistics and delivery is a key consideration. According to the US Environmental Protection Agency, in 2021 the light / medium / heavy duty truck segment emitted almost 1.1 billion metric tons of CO₂ equivalent [5]. The transportation sector is responsible for 29% of US GHG emissions. The logistics / delivery industry is a key contributor to this total. The trucking industry is slowly moving toward electric truck fleets, but this will take decades.

2.4 LABOR CONTENT

Labor content is a key challenge for the delivery industry. Delivery truck drivers are difficult to recruit, and often have quality of life issues like long hours, injuries, and stress. There are numerous demonstrations of autonomous ground delivery vehicles, but their technology is not ready for the volume deployment needed to improve the labor situation.

Drone-based networks will be largely autonomous, delivering cargo automatically to a structured receiving location near the customer – eliminating the “running to the front door” delivery people in trucks must do.

2.5 CARGO SECURITY

There are challenges in the security of delivery networks. “Porch pirates” stole an estimated 260 million packages in 2022, costing billions of dollars in losses [6]. Today’s delivery networks are not secure enough to carry high-value or controlled goods. Medical deliveries are a particular challenge, for example delivering schedule 1/2 drugs from pharmacies to remote clinics or returning biological samples from remote clinics to central labs. There are similar security challenges for drones carrying currency, jewelry, evidence or high value goods. The ideal solution would be so secure that the end-to-end delivery system was capable of maintaining chain-of-custody tracking of sensitive deliveries and evidence that would be admissible in court.

2.6 SCALABILITY

Drone delivery networks must be scalable. Their initial deployment is typically a modest proof of concept / limited technical trial with a few drones and a few landing points over a small geographic area. As technical confidence, regulatory maturity and consumer trust builds, these networks will be expanded to cover larger geographic areas, longer flight durations, heavier and more critical cargo, more diverse weather conditions, and many more delivery missions per hour. Ultimately, a drone delivery network could scale to cover the entire metropolitan area of a large city, have tens of thousands of simultaneously active drones servicing tens or hundreds of thousands of loading / landing endpoints, and flying hundreds of thousands of largely autonomous delivery missions per day. This could provide an economic value of hundreds of millions of dollars per year for the delivery service operator(s).

2.7 REGULATION

One large impediment to near-term deployment of large-scale autonomous drone delivery networks is government regulation of drones. Trust is slowly building in drone technologies (some jurisdictions faster than others), but in general, drone operations require a licensed pilot (for example, with what is called “Part 107 Certification” in the United States) to maintain visual line of sight with the flying drone at all times.

The United States Federal Aviation Administration regulations Part 135 has special rules for cargo delivery via drone [7]. Flight scenarios are carefully regulated, with restrictions for flying over people or critical installations, flying at night, altitude restrictions and many other rules. Obviously, if the drone’s mission is to deliver medical supplies to a jungle clinic or hot pizza to a college dormitory, this visual line of sight, night-time operation or flight over people restrictions are serious obstacles to high-scale deployment delivery network deployment. Fortunately, aviation regulators worldwide are currently crafting new, less restrictive rules for drones, and with their anticipated implementation in the next year or two, fully autonomous drone delivery networks should take off [8].

2.8 COST

Cost is key, with many drone delivery networks seeking to deliver a typical package for less than \$1US [9]. As autonomous drone fleets are deployed at high scale, the cost of last-mile delivery will be a less significant portion of the total costs of logistics. Lower cost deliveries enable many innovative commercial scenarios.

All the motivations and challenges described in this section impact the drone delivery network architecture and elements described in Chapter 3 Drone Delivery Networks and Chapter 5 Drone Cargo Delivery Network Elements.

3 DRONE DELIVERY NETWORKS

Delivering packages through the air via a network of autonomous drones is a compelling alternative to traditional truck-based logistics networks. It can avoid traffic congestion, much of the greenhouse gas emission, labor shortages, cargo security concerns, and can be an order of magnitude faster than truck-based alternatives. Of course, with these advantages comes significant complexity, especially in the integration of hundreds of types of IoT sensors and actuators, a hierarchy of sophisticated computing resources, and millions of lines of software.

This section discusses several components of a complete drone delivery network, including drones with cargo management capabilities, various ground support systems for cargo loading and unloading (including landing pads, drone docks, smart postal boxes and robotic warehouses), other ground support systems (including weather and air traffic sensors, wireless network base stations, security screening devices, etc.), and the multi-layer digital control structure. The drone

IoT Techniques and Elements for Drone Package Delivery Networks

delivery network is a system-of-systems, where individual components are first designed and integrated, and then the entire system is integrated and commissioned.

Figure 3-1 is an overview of the components of a drone cargo delivery network. The details of each of these components will be described in subsequent sections, along with the IoT sensors, actuators, computing and networking that support them. Of course, the drones actually carrying the cargo are central to the network architecture. They come in many sizes, with takeoff weights ranging from under 250g (0.55lbs) to heavy-lift cargo drones with cargo capacity up to 225kg (almost 500lbs) [10].

Various types of structured landing pads, drone docks, robotic mailboxes, and automated warehouses load the cargo onto the drones and receive it at the delivery location. Additional radio and sensor elements provide wireless and wired network connectivity, weather sensors, and monitoring the performance and safety of the airspace and delivery system. Eventually, these networks could contain security screening systems similar to airports that make sure the drones and the cargo they carry are safe, even for operation over heavily populated areas.

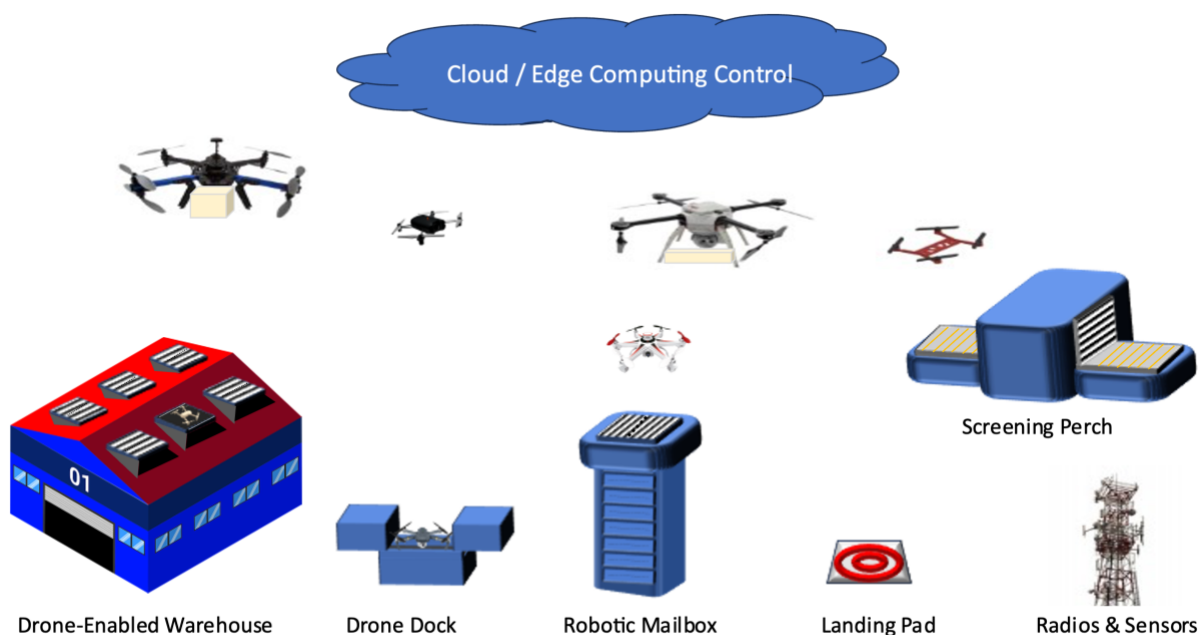


Figure 3-1: Drone cargo delivery network components.

4 USE CASES

Examples of use cases for this network can be addressed in various service domains.

4.1 MEDICAL CARGO / LAB SAMPLES

One of the earliest applications of drone delivery is medical. Remote clinics may be only a few kilometers from a large central hospital, but due to traffic or terrain, it may take hours for a

critical delivery by road vehicle of drugs or medical equipment. Drones can shorten that time to minutes. Zipline is a good example of a system with success in medical deliveries, making over 7 million deliveries by drone since 2016 [11]. Drone medical delivery systems are also valuable in the reverse direction, to bring bio samples from the remote clinic to a central lab. Security is key to medical applications, to control access to regulated drugs, or to ensure an unbroken chain of custody for the lab samples.

4.2 FOOD DELIVERY

Another use case is fast food delivery. Restaurants prepare meals and load them onto drones, which fly the food to wherever the recipient is located. The speed of this system will be much faster than traditional road-based food delivery networks like DoorDash, GrubHub or Uber Eats, greatly improving food quality and customer experience.

4.3 MILITARY LOGISTICS

Military logistics is another important use case. A single flight of a mid-size drone with 5kg payload capacity can move about 8 MREs (Meals Ready to Eat), 20 units of blood plasma, 5 liters of water or 190 rounds of 7.62mm NATO ammunition to front-line troops, without endangering delivery drivers. Many other use cases in military / government logistics are being explored.

5 DRONE CARGO DELIVERY NETWORK ELEMENTS

5.1 CARGO DRONES

Many companies worldwide manufacture commercial drones, including DJI [12], Parrot [13] Skydio [14] and Wing [15]. Cargo drones come in several categories, typically organized by maximum takeoff weight.

Table 5-1 shows the categories recognized by the US FAA [16] (other jurisdictions have slightly different limits). The under 250-gram takeoff weight Category 1 has too small a cargo capacity (typically under 100 g) to be useful for mainstream cargo deliveries beyond niche applications like replacing lost golf balls on the course or delivering small bottles of medication.

Most mainstream cargo delivery networks will use Category 2 or 3 drones between 250 g and 25 kg maximum takeoff weight, with the ability to transfer 11-25 ft-lbs of kinetic energy (a measure of their potential to injure people) with a maximum cargo capacity in the 10 kg (22 lb.) range. This is adequate to replace 70% of the truck-based deliveries done by companies like Amazon and UPS. Heavy lift cargo drones with a takeoff weight over 25 kg are uncommon, but gaining some use in things like construction, ship-shore services, and scientific deliveries.

Categories Recognized by US FAA		
Category	Weight/Max. Energy Transfer	Comments
1	Under 250 Grams / 0.55 lbs	Hobby, aerial photography, surveillance
2	Max of 11 ft-lbs Energy	Smaller cargo deliveries, typically in the 5 kg payload / 10 kg takeoff weight range
3	Max of 25 ft-lbs of Energy	Large cargo deliveries, typically in the 10kg payload / 25 kg takeoff weight range
4	Special Certificates for Heavier / Specialized Drones	Heavy lift drones, construction

Table 5-1: Categories of drones.

Figure 5-1 shows the anatomy of a typical cargo drone. The following subsections describe them in detail.

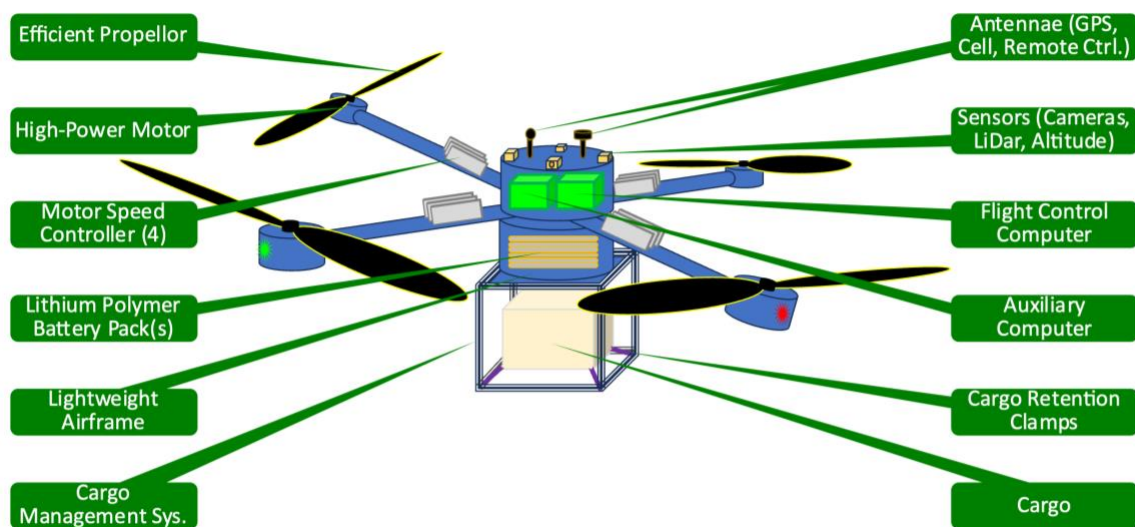


Figure 5-1 Elements of a typical cargo drone.

5.1.1 ROTORS (PROPELLERS + MOTORS)

Drones have several aerodynamically efficient propellers that are directly driven by brushless electric motors. Four and six rotor configurations are common (called quadcopters and hexcopters, respectively), but other numbers are possible for specialized flight characteristics. Even / odd numbered rotors typically turn in opposite directions, and by carefully coordinating and controlling the speed of all rotors, flight maneuvers including pitch, yaw, roll, translation in four directions and altitude changes are achieved.

The electric motors are connected to motor speed controllers that commutate the motors to run them at the commanded speed and power. A typical motor controller for a mid-size cargo drone might have 80-amp outputs per motor running at about 22 volts, for a theoretical maximum

power approaching two kilowatts per motor (although in level flight, they will only use a fraction of this).

5.1.2 BATTERIES

Batteries are a critical component of the drone. Lithium polymer batteries are the standard, as they have the best mix of weight, total energy stored, and total power for drone applications of widely available battery chemistries. There is a constant tradeoff between the weight and size of the batteries, the cargo capacity of the drone, and its flight characteristics (speed, range, maneuverability, etc.). Most of the battery energy goes through the motor speed controllers to the motors and propellers, but a small fraction is used to run other loads like processors, cameras, sensors, lights, and cargo management systems.

Typical cargo drones balance the energy to provide about 30 minutes of flight time with their maximum rated payload weight at a typical cruising speed of 40-80 km/h. This creates an operational round-trip range of 10-20 km without remote recharging. Of course, if some payload weight is sacrificed to carry larger capacity batteries, this range can be extended, to a point. Hydrogen fuel cells are a promising energy storage technology for longer-range drones.

5.1.3 FLIGHT CONTROL COMPUTER

The next important subsystem of a drone is the flight control computer. The primary task of the flight control computer is to accept pilot / autonomous control commands, read a collection of sensors, and provide digital command signals to the motor speed controllers for each rotor. Pilot commands can be direct inputs from live joysticks controlling pitch, yaw, roll speed, direction and altitude.

However, most modern cargo drones have some form of autopilot that accepts commands at a higher level. For example, “take off from the current location, ascend to ZZZ meters, and fly to a waypoint at GPS coordinates (XX,YY).” By stringing together several waypoints, a flightpath can be assembled to move the drone to the desired destination, while avoiding terrain, obstacles or restricted flight zones. Then, after hovering at the last waypoint, precision landing systems can automatically bring the drone to a safe touchdown to load or unload its cargo.

A number of sophisticated IoT sensors feed flight related information into the flight control computer. Gyroscopes measure the pitch, yaw and roll angles and rates of change, accelerometers measure acceleration in three axes, and the algorithms in the flight control computer compare these readings to desired values and change the motor speed settings to correct errors between commanded and measured states. Magnetic compasses are sometimes employed to find headings, but their accuracy is often disturbed by metal or magnets in the cargo. Absolute position sensors typically use Global Navigation Satellite Systems (GNSS) like GPS (USA), GLONASS (Russia) or Galileo (EU) to fix their position with a typical accuracy of about five meters [17].

If more accuracy is required, differential techniques such as Real Time Kinematics (RTK) can be employed, where a local receiver (sometimes attached to a cell tower or drone mailbox) reads the GNSS position indicated for a known location, and broadcasts corrections to the drone [18]. The Verizon RTK system is one example that can routinely achieve centimeter-level precision [19], making it useful for precision landing, where uncorrected GNSS would not be.

Altitude over ground is another important sensor reading for the drone flight control algorithms. Several alternative altitude determination systems are in common use, sometimes in combination, including: GNSS with RTK, RADAR altimeters, LiDAR altimeters, barometric altimeters, ultrasonic range finders, integration of Inertial Measurement Unit (IMU) outputs, and down-pointing depth cameras [20].

The flight control computer uses all these IoT sensor readings to maintain stable flight, and to direct the drone between waypoints. Many drones also have sensors to report battery voltage, current, temperature and charge state, motor performance, and various internal and environmental measurements. Streams of telemetry from these sensors are made available to auxiliary computers and downlinked to ground networks.

5.1.4 AUXILIARY COMPUTERS

Many cargo drones, especially those intended for autonomous operation use a powerful auxiliary computer to supplement the flight control computer. These are typically multicore or GPU processors optimized for special functions, such as analyzing camera feeds, detecting hazards, precision location of landing positions, advanced mission planning, and supporting formation flying. These are typically fully realized edge computers, with operating systems, middleware, protocol stacks, AI inference capabilities and full cybersecurity.

As a concrete example, the auxiliary computer in many autonomous drones run the sense-and-avoid algorithms, where a number of attached cameras view the drone's surroundings, and the auxiliary computer continuously analyzes the images to determine the drone's position, altitude, and if any obstacles (like human piloted aircraft, other drones, birds, vegetation, power lines, etc.) are in the flight path. If hazards are discovered, the auxiliary computer automatically commands the flight control computer to make evasive maneuvers to avoid the hazard, then return to course.

NASA's Independent Configurable Architecture for Reliable Operations of Unmanned Systems (ICAROUS) is an excellent example of sense-and-avoid [21]. Auxiliary computers are also sometimes used for flight and fleet optimization calculations that try to improve the speed, energy efficiency, safety, reliability, range, performance and resource utilization of large-scale delivery networks.

5.1.5 NETWORK CONNECTIONS

Network connections are essential to drone delivery networks to command the drones where and how to fly, and to report their position and status to the system. Drones typically include bidirectional cellular modems to connect them to cellular base stations on the ground, and thence to the Internet backbone. Reliability of these connections is a concern, because if the connection between the drone and ground networks is lost, many key capabilities are compromised, so redundant networks and autonomous fallback functions are often provided.

Most drones also have additional radio systems for flight control / telemetry that connect the drone to the remote controls used by a human pilot, or ground-based navigation systems, and downlink real-time video camera images (called FPV, first-person views) to the ground. Sometimes when a drone is landed, yet another wireless link (often Wi-Fi) is used to upload large databases like flight plans and terrain maps into the drone in preparation for the next mission, and download mission logs, video and sensor telemetry from the previous mission. Some drones can receive various location beacon and positioning data streams using specialized receivers.

Finally, remote ID transmitters have recently been required by US FAA part 89 rules [22] for most cargo drones so authorities can determine the exact location of the drone and its pilot, verify drone ID information, and receive various flight parameters.

5.1.6 AIRFRAME

The drone airframe provides mechanical support for all the drone components and is typically made out of lightweight, strong materials like carbon fiber tubes and aluminum fittings. Mounting points are provided for the rotors on arms, the batteries, computers, sensors and cargo management system components. Landing legs / skids mechanically interface the drones to their ground support systems when they land.

5.1.7 CARGO MANAGEMENT SYSTEM

The final element of the cargo drone is the cargo management system. When a package or other cargo is loaded onto a drone (either manually or via robotic actuators), this system detects the presence of the package, and using various methods retains or latches it securely so it won't fall off as the drone flies. Once the drone has reached its destination, the cargo management system gently releases the cargo onto a landing pad or into a robotic package receptacle. There are several variants of cargo retention systems in use.

Sometimes, packages are completely contained within the drone's airframe, using "bomb bay doors" or similar techniques to protect, retain and release the packages as necessary. Some drones use external clamping mechanisms driven by servo motors or other actuators that clamp, support and secure the cargo under the airframe. Some delivery drones use a winch scheme, where the package is attached to a hook, and can be lowered on a cable while the drone hovers

several meters above the delivery location. A release mechanism detaches the cargo on contact with the ground or landing surface.

5.2 LANDING PADS, DRONE DOCKS SMART DRONE MAILBOXES AND AUTOMATED WAREHOUSES

Drone delivery networks typically need a structured device to load or unload packages. These could be simple, passive landing pads, drone docks / drone-in-a-box solutions, robotic smart postal boxes or a fully integrated warehouse solution. There have even been experiments with mobile landing systems, some acting as remote warehouses [23], some able to send and receive packages from moving vehicles [24].

5.2.1 PASSIVE LANDING PADS

The simplest ground support system is a passive landing pad. These are typically receivers only, and don't have provisions to shelter drones or packages, recharge drones, or provide enhanced security or safety. Their form could be a heavy mat that the package recipient places outdoors in a clear, reasonably secure location away from people and animals.

They often contain some printed fiducial such as a QR code that the drone can recognize during final approach (using its down-pointing camera), verify the recipient and use for final landing guidance. The drone may perform a full rotors-stop landing, unload the cargo onto the pad, and take off. Or it could do a "touch and go" delivery where the drone pops down onto the landing pad briefly, and a contact sensor automatically triggers the release of the package.

Winch systems can use these landing pads as targets to direct their cargo hooks from many meters above. Some advanced versions of landing pads have lights or beacons to aid night deliveries, and security systems to monitor pad and cargo status. A big disadvantage of this approach is that there is no physical separation between the drones and people / animals on the ground, they don't solve the "porch piracy" problem of stolen packages, and don't enable the loading of packages (for bidirectional logistics, medical samples, customer returns, etc.).

5.2.2 DRONE DOCKS

Drone docks are structured active landing systems that provide more support infrastructure for the drones. They are sometimes called "drone in a box" solutions because they integrate drones with fixed location boxes that service them. Some active manufacturers in this space include: Skydio [25], Dronehub [26], DJI [27] and Nokia [28].

Drone docks typically have a weather cover that opens to receive a landing drone, and then closes to completely contain it. This protects the drones from extreme weather and secures them from theft and vandalism. Drone docks usually have automated charging or battery swap functions that replenish the energy reserves of the drone parked within them. They often have fast, secure

and reliable upstream and downstream network connections to support the efficient upload and download of data between the drone's onboard storage and the Internet backbone.

Some drone docks have external sensors to measure weather conditions or sky survey cameras whose readings are reported to the network control systems. Some drone docks are developing capabilities to swap drone payloads, but they usually don't have the advanced management capabilities of smart drone mailboxes.

5.2.3 SMART DRONE MAILBOXES

Smart drone mailboxes usually contain the sheltering, charging, networking and sensing functions of drone docks, but also contain advanced cargo management systems. As shown by the examples of smart mailbox products from companies like Antwork [29], Valqari [30] and Matternet [31], they are typically tall enough (over two meters) so people on the ground are physically separated from the elevated drone landing pad, improving the safety of bystanders.

They often contain centering mechanisms that mechanically shove the drone from its slightly imprecise landing location to a specific position on the landing surface to align the cargo management systems of the drone exactly with the mailbox's cargo manipulation robotics. They often have a cargo hatch that separates the landing surface from the interior of the mailbox. Robotic actuators open the hatch, and an elevator-like mechanism reaches through it to interface with the drone's cargo management system and moves the cargo to various destinations inside the mailbox. Smart drone mailboxes typically have one or more secure package lockers capable of receiving outgoing cargo from humans, and robotically loading it on the drone, or receiving packages from a drone and securing it in a locker for later collection by a human.

A few smart mailboxes, for example the system developed by Antwork, have interfaces between aerial drone delivery systems and autonomous ground vehicle delivery systems, capable of bidirectionally exchanging cargo between autonomous vehicles for both air and ground delivery modes.

A large advantage of these robotic, multi-locker drone mailboxes is that only the humans authorized to access a specific package can touch it (the lockers won't open for anyone without the proper credentials), and no human can access the cargo within the mailboxes or in flight on a drone. Porch piracy is eliminated, and package custody can be rigorously tracked throughout the delivery process.

5.2.4 DRONE-ENABLED WAREHOUSES

The above ground support systems are most suitable for the distributed endpoints of a drone cargo delivery network, spread across the landscape to be conveniently close to cargo recipients. However, for large-scale central warehouses, fulfillment centers or delivery kitchens, those solutions may not be optimal. One could use several (or several dozen) modified smart drone mailboxes, a dispatch system that manages which deliveries go into which lockers, coordinates a

large fleet of drones, and instructs the humans that pull cargo from the warehouse and load the lockers.

An alternative would be a specialized large-scale system, or “roost” at the central location that is capable of sheltering, charging, and fully automatic loading of a fleet of dozens or hundreds of drones. The conveyor belts typically found in large-scale logistics hubs would be extended right into the roost and the speed, energy, and labor content of the drone deliveries would be optimized. The OpenFog Consortium (part of the Industry IoT Consortium since early 2019) considered high-scale drone delivery architectures and their computational challenges and produced a video of some operational scenarios [32]. As the OpenFog Consortium no longer exists, the reader is directed to the IIC Edge Computing White Papers site [33] for additional information.

5.2.5 SENSORS AND ACTUATORS

As you can imagine, all these sophisticated drone support functions require many IoT sensors and actuators. Every place where a part of a drone touches a ground resource could have a sensor to validate the presence and alignment of the mechanical elements, and often force or weight sensing is helpful.

This can be implemented as simple mechanical switches, optical / magnetic proximity sensors, force sensors or strain gauges. The robotic actuators that move mechanical elements of the docking stations / mailboxes / warehouses need position feedback to verify their alignment, and often force feedback to be sure no mechanical collisions, debris fouling, motor overloads or misalignments are occurring.

This can be implemented by specialized sensors like optical range finders, Linear Variable Differential Transformers (LVDTs), strain gauges, proximity sensors, linear or shaft encoders, etc., or can be inferred by knowing how far and with how much power the robotic motors are being driven. If a drone is being charged while landed, charging current, battery cell voltage and battery temperature are sensed as useful indicators of energy transfer. Multiple temperatures are often monitored in the ground support equipment, including the temperature in the drone storage compartment under the weather covers, temperature inside the mailbox or in warehouse passages, and (especially if cooled or heated cargo is being carried) the temperature of each cargo storage locker.

Many sensors also monitor the outside environment to facilitate safe drone operations, including temperature, barometric pressure, wind speed, wind direction, visibility distance, radio environments and sky survey cameras to verify the airspace is clear before takeoff. Many types of actuators complete the IoT package for drone ground cargo management elements, including lights, beacons, multiple types of motors / linear actuators, fans, pumps, heaters, coolers, power switching devices and radio transmitters.

5.3 OTHER GROUND SUPPORT RESOURCES

To build a trustworthy drone delivery service at high scale, a few other ground support elements that are not directly related to cargo management may be needed. These include wireless networks base stations, air traffic control sensors, and security screening devices.

5.3.1 WIRELESS NETWORK NODES

The various types of landing pads can be supported by wired networks (and probably should be, to support the bandwidth, reliability, security and privacy they require, and to preserve radio spectrum for the drones). This will typically use distributed broadband access network elements for DSL, DOCSIS / Cable and fiber-based telecommunication networks) and connect to these networks as additional endpoints.

However, drones themselves obviously can't use wired networks in flight, and therefore must use wireless communications networks to stay in touch with their pilots (if used) and the layers of autonomous operation support processors. There are two broad categories for air-ground wireless networking: licensed RF spectrum and unlicensed RF spectrum. In licensed radio networks, the radio frequencies used are reserved by government license for a specific network. Examples include 4G / LTE / 5G cellular networks, and satellite networks.

Unlicensed radio systems don't dedicate frequencies for specific uses or transmitters but use shared radio spectra that are vulnerable due to interferences by unknown number of users. Examples include Wi-Fi, Bluetooth, LoRaWAN, Sigfox, and the remote-control uplink and video downlink systems used by most commercial drones. Because of the critical reliability and security requirements of drone delivery services, most systems in operation today use licensed spectrum for their critical control and telemetry uplinks and downlinks – usually 4G or 5G cellular, and unlicensed bands are not recommended for critical drone communication links.

5.3.2 SENSOR ARRAYS

Various sensor arrays help keep the airspace safe. Weather sensor networks measure temperature, wind speed and direction, visibility distance, and other parameters. These readings from multiple sensing locations can be fused into a map so a drone knows if it is safe to take off and what to expect ahead on its flight plan. There are cameras, RADAR and LiDAR systems that scan the sky for drones, piloted aircraft, bird flocks, hazardous weather and other conditions that could impact drone operations in the area.

Microphone arrays can be trained to recognize the sound of drones and other aircraft and measure their approximate heading. Radio transceivers can identify the bearing of any flying radio source. Radio transponder systems can send out interrogation signals, and wait for any drones or aircraft in the area to respond with their position, velocity, heading, altitude, etc. Remote ID systems require a drone to broadcast certain information about its position and status.

Taken together, these different sensing modes represent a sensor fusion system, capable of giving much more complete situational awareness for an airspace than a single sensing modality could. If a drone is detected by these sensors, but it is not registered in the flight plan database or on its planned course, it could be a rogue drone performing unauthorized missions, carrying dangerous or contraband cargo, or have a navigation malfunction, and the appropriate authorities are immediately notified to consider countermeasures against it.

5.3.3 SECURITY SCREENING DEVICES

As drone cargo delivery becomes mainstream, there are certain problems that must be avoided. Unfortunately, cargo drones in the 10 kg payload class are effective weapons and smuggling platforms, and society's bad actors may exploit them. The passenger aviation network uses security screening authorities (the Transportation Safety Administration in the USA, and the European Union Aviation Safety Agency are examples) to run checkpoints at airports to ensure the safety of air travel.

Autonomous cargo screening of drones is possible using a device called a screening perch. Think of it as two landing pads connected by a conveyer belt located at a geofence boundary between a region of lower and higher security.

The drone lands on the low security side, is retained on the conveyer belt by mechanical or magnetic means and is passed through many scanning devices (scales, X-Ray, Millimeter wave, explosive / narcotics sniffers, flight software validation, etc.). If the sensor readings match the type of drone and its cargo as declared on the flight plan, it continues to the opposite landing pad and is launched on its way into the more secure area. Conversely, if some abnormality or dangerous condition is detected, the conveyer belt firmly captures the suspect drone and moves it to an isolated bunker for the authorities to more closely investigate. An example of this architecture can be found in US patent 10,167,092 [34].

5.4 CONTROL / COMPUTING RESOURCES

The final important component of the end-to-end drone cargo delivery resources is a hierarchy of computational resources needed to control, manage and coordinate all elements and secure the cargo throughout the network. It includes computation and storage resources flying on the drones, in the various ground support systems, and layers of edge / cloud computers integrated in the network.

We already discussed the two layers of flying computational resources (flight control computers and auxiliary computers) that are responsible for the real-time operations of the drone, and the interface with all the drone-carried sensors and actuators. These computers need response times on the order of one millisecond to maintain stable control of the airframe and react in time to avoid obstacles while traveling at high speed. These computers are interconnected with ground support elements via wireless network links.

5.4.1 GROUND SUPPORT PROCESSORS

The next layer in the control hierarchy are the various processors found in the ground support equipment. They run the robotic drone and cargo management systems of drone docks, smart mailboxes and automated warehouses. They also optimize and coordinate the local functions of the drone fleet (managing charging profiles, for example), and maintain adequate security of the drones and ground resources. Specialized ground support systems like sensor arrays or screening perches will have sophisticated processing resources associated with them capable of running complex algorithms, including AI inference.

5.4.2 EDGE COMPUTING

Next in the hierarchy are one or more layers of edge computers. Their function is to coordinate all the critical functions across the network of multiple drones and ground support elements. They typically are assigned the tasks that can't be accomplished in the cloud due to constraints on low latency, network bandwidth, security, privacy, reliability or data gravity (the need to store and process data physically near where it is generated or consumed).

Edge gateways are one example of edge computers, typically with modest compute capacity optimized for protocol translation or the interconnection of disparate network types. One very promising type of edge computer associated with cellular base stations is called Multi-Access Edge Computing, based on the ETSI MEC standard [35].

The MEC nodes are extensions of the cloud, and are located at or near cellular base stations, and have computational resources valuable for functions like drone fleet coordination, emergency response, or end-to-end security monitoring. Finally, some Content Delivery Networks (CDNs) are building out edge computing resources to supplement their usual web caching functions. They are logically a somewhat more widely distributed cloud and are potentially valuable for coordinating drone operations on a city-wide level.

5.4.3 CLOUD COMPUTING

The top of the system control hierarchy is cloud computing, where much of the service logic, AI, monitoring, ordering, billing, and digital twin simulation is located for the entire network. Cloud computing could be public (i.e., Amazon, Microsoft, Google), private, or hybrid.

The cloud cooperates with the various layers of edge, endpoint and drone-based resources to optimize on which level of the compute hierarchy all parts of the algorithms and data structures are optimally located. And, as delivery service mixes change, or if various faults, overloads or cybersecurity attacks are observed, the compute hierarchy can dynamically move data and algorithms between levels of the hierarchy in an attempt to continue nonstop safe operation of the network.

5.5 CARGO DELIVERY FLOW

Figure 5-2 is a flowchart showing a typical cargo delivery mission using drone mailboxes on both ends (alternative scenarios are possible). It begins with the creation of an e-commerce order for goods to be delivered, where “drone delivery” is the selected option. The order is transmitted to the drone network, and a negotiation takes place to finalize the physical locations, users, cargo specifics and times involved. Assuming the drone network can fulfill the request, a dispatch order is created. A drone with adequate cargo lift capacity, speed, flight envelope and energy reserve is selected, and flies autonomously to the sending location, where it typically precision lands on a smart postal box or warehouse system.

The package is moved from the locker or warehouse stock by robotic subsystems and secured to the drone’s cargo retention system. The drone makes several pre-flight tests, including flight computer self-test, battery reserve test, and electronic negotiation with aviation authorities to file and approve a digital flight plan.

Once takeoff permission is received, the drone takes off to the prescribed altitude (typically around 100 m / 300’ above ground) and autonomously navigates through a series of waypoints (potentially avoiding obstacles or restricted areas as it goes) until it is hovering over its destination. It then uses its position, altitude and image sensors to perform a precision landing at the recipient’s landing facility (or alternately does a winch or touch-and-go delivery). At this point, the drone can be secured, sheltered and recharged for an extended stay within the drone mailbox’s weather covers, or it can just drop off the cargo and request clearance to leave immediately.

Robotic equipment can move the cargo from the landing pad to a secure package locker, and the recipient is notified of its arrival. The recipient goes to the landing location, enters credentials to verify the correct identity, the selected locker opens and the package is retrieved. At that point the delivery is complete, and billing records are created for the goods and the drone service that delivered them. Hundreds of IoT sensors and actuators and a hierarchy of multiple levels of computers enabled this scenario.

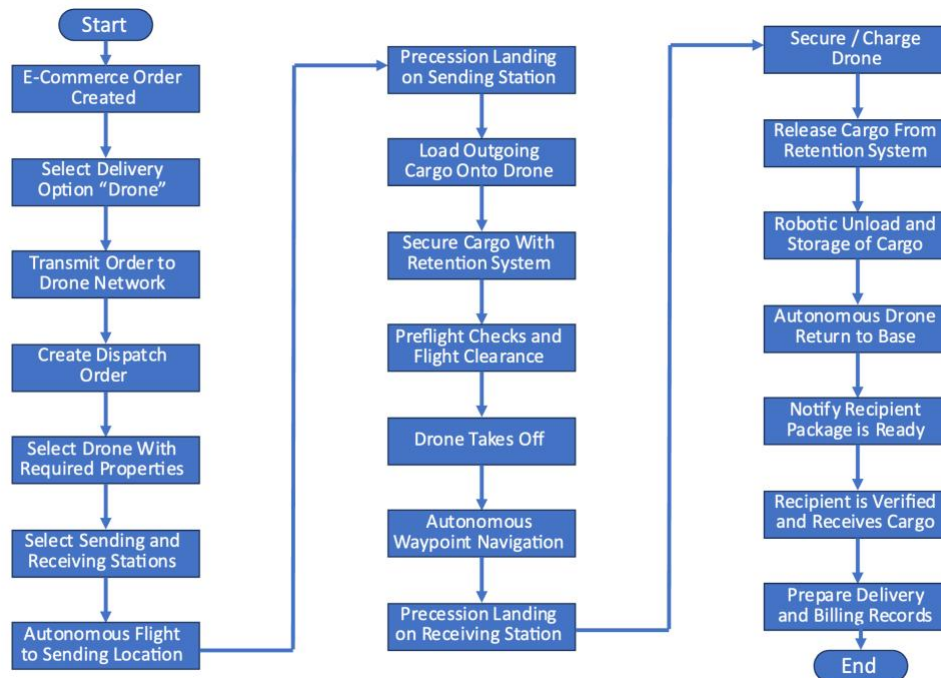


Figure 5-2: Cargo delivery flow.

6 CONCLUSIONS

Drone cargo delivery networks are an important emerging trend in logistics. They could handle about 70% of the cargo delivered by mainstream freight delivery companies, greatly reducing the time, cost, labor content and greenhouse gas emissions of truck-based logistics.

IoT techniques are essential to the operation of these networks. IoT Sensors monitor many parameters in drones, cargo, ground support systems and the airspace. IoT Actuators allow digital systems to control the flight parameters of drones, and the robotic functions of ground support systems that manipulate the cargo.

Hierarchical computer resources, including flight control computers, auxiliary drone processors, ground support processors, several layers of edge computing and the cloud, all interconnected with various IoT networks provide the IoT intelligence needed to integrate the entire network. The deployment of these autonomous drone cargo delivery systems at scale is poised to disrupt the global logistics and delivery industry.

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