UNIVERSITY
OF TURKU

Exploring the application and integration of UAV technology in delivery systems

Mechanical engineering
Bachelor's thesis

Author(s):
Aleksander Gävert

22.04.2024
Turku

Bachelor's thesis

Subject: Drone usability in delivery systems
Author(s): Aleksander Gävert
Title: Exploring the application and integration of UAV technology in delivery systems
Supervisor(s): Professor Wallace Moreira Bessa
Number of pages: 23 pages
Date: 22.4.2024

The bachelor's thesis 'Exploring the application and integration of UAV technology in delivery systems' discusses the world of autonomous UAV aircraft and how to integrate such technology into delivery systems. The research begins by explaining thoroughly how different airframes operate and their strengths and weaknesses. By proposing a dock that combines both FMS (Flexible Manufacturing Systems) technology and automatization, drones become a viable and useful alternative to car-based delivery systems. Drone based delivery systems have a smaller carbon footprint per delivery kilometre, are faster, and more flexible when comparing fossil fuel hungry car delivery methods. Using an inductive structuring, the thesis discusses aerodynamics, sensor requirements, and hypothetical delivery system based in the city of Turku Finland. In this study the thesis deducts which sectors would benefit from such delivery systems by interviewing personnel from those sectors. The analysis extends to considerations of infrastructure requirements and the environmental advantages of drone deliveries. The research also addresses critical aspects such as autonomy, navigation, obstacle avoidance, traffic control and the essential sensors needed for efficient drone operations. By looking into possibilities in quick response delivery systems and delivery time reductions, the thesis explores the potentials of drone deliveries and automated logistics. Despite regulatory and technical limitations, the thesis lays the groundwork for future delivery systems. While acknowledging the lack in regulations, infrastructure, demand, and lack of financing incentives and technology, the thesis concludes that the adoption of drone delivery systems is still something to invest in. This technology opens new greener possibilities in societal infrastructure, such as flexibility, efficiency, and environmental benefits and paves the way for a new era of lifestyle improvements.

Key words: UAV, Drone, Delivery system, Aerodynamics, Fixed-wing aircraft, Rotary-wing aircraft.

Key questions:
1. What are the different types of drones, and what are their strengths?
2. How can multiple drones operate in the same airspace at the same time?
3. How does drone delivery system work?

Table of contents

1 Introduction 4

1.1 Thesis objectives 4

1.2 Research methods 5

2 Aircraft design 6

2.1 Fixed wing aircraft 6

2.2 Rotary wing aircraft. 8

2.3 Choosing the right design 10

2.4 The hybrid approach 11

3 Drone delivery 12

3.1 Different delivery mechanisms 12

3.2 Last mile delivery system. 13

3.3 Safety 13

4 Autonomy 15

4.1 Navigation 15

4.2 Obstacle avoidance 15

4.3 Some of the required sensors 16

4.3.1 GPS 16

4.3.2 Pitot tube 16

4.3.3 IMU 16

5 Hypothetical delivery system 18

5.1 System design. 18

5.2 Package handoff 19

5.3 Internal mail service. 19

5.4 Airspace regulations 20

6 Conclusion 21

7 References 22

1 Introduction

In the past years UAV technology has evolved rapidly and it doesn’t look like it’s going to stop [1]. The world is seeing companies try to produce viable and profitable solutions to utilize drones. There are many practical benefits from a city-wide drone delivery system, and many public service sectors would benefit from such systems [2]. Not only is drone delivery greener in urban areas than ground based truck delivery methods when comparing in parcel-km, it also can enable very flexible time schedules [3]. With proper infrastructure in place a warehouse could send out a parcel within an hour. The parcel flight time could be quite small, when considering the drone can fly directly to its destination at around 100km/h without being affected by traffic. This brings up new cost-effective opportunities in unscheduled time sensitive shipping, which cannot be realistically achieved with a car-based system. There are still technical limits to this technology, such as power density of batteries or regulatory deficiencies in the European union Aerial Safety Administrations (EASA) regulations. The category that contains drone delivery systems, certified category [4], is still in its proposal stage. EASA has not yet submitted a proposal that the EU would approve.

1.1 Thesis objectives

This thesis is structured in an inductive manner. First three chapters (2-4) consist of literature review. The review will explain aerodynamic capabilities of fixed wing and rotary wing drones and their comparative strengths and weaknesses. It will also explain how one could build a hybrid model of these two main airframes. The review explains in detail how these airframes generate lift and stay stable in flight in the view of passive and active stabilisation. The next chapter will explain how to use these airframes for drone delivery. Chapter 3 consists of some literature review combined with my own introspection. This chapter will venture into different delivery methods and their logical drawbacks. After this the thesis will explain what sensors and electronics the drone needs to fly and navigate. Chapter 4 is based on literature review solemnly.

After explaining the flight mechanics of different drone types, I will create a hypothetical drone delivery system in the city of Turku, Finland. This exercise will take parameters from already proven concepts like the WING delivery system [5]. Turku is chosen for accessibility to information regarding the city. This exercise will not consider the city’s small population. After proving that the city of Turku would benefit from this type of delivery system, it can be deducted that city-wide drone delivery systems are beneficial. By making this observation it can be further deducted that it would work in other cities as well.

1.2 Research methods

This thesis has used UtuVolter and Google scholar for scientific research. There are citations of some other sources like company websites and Wikipedia for statistics. This subject is still quite fresh and is gaining a lot of momentum. Figure 1 shows the number of published papers (Scientific Articles, -books, and -blogs) that contain the search word “UAV” and “Drone delivery system”.

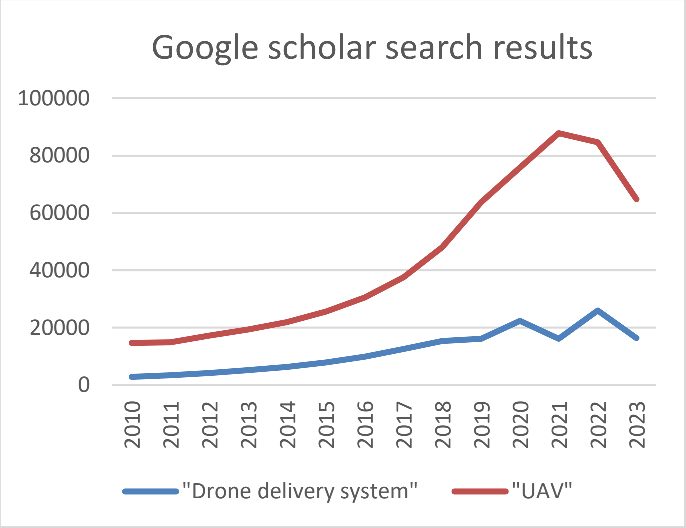

Figure 1: Graph of pupblished papres.

2 Aircraft design

There are many diverse types of UAV airframes that have been designed to complete a very specific mission. These airframes can be classified into three main sectors. When inspecting UAV design, there are clear design choices that have been made for the UAV's specific mission. The sectors are consumer, agriculture, and surveillance/mapping. There are also two main types of airframes, fixed wing, and rotary wing aircraft. Both designs have their own unique strengths and weaknesses. The drone's airframe must be designed with its specific mission in mind for the wanted outcome. There is no "do it all" airframe that would work in every mission type.

2.1 Fixed wing aircraft

Fixed wing aircraft have considerably better range and speed than regular rotational wing aircraft.

This is linked directly to the design choices of the airframe [6]. Lift comes from wings that travel through the air. By analysing lift-to-drag ratios (or L/D) of different aircraft, it becomes clear that L/D is always bigger than 1 in stable flight (see Fig.2) [7]. This means that the force needed to overcome the drag of the airframe is smaller than the generated lift of the wing. This phenomenon enables stable flight with engine power that provides less thrust than the weight of the vehicle. Smaller thrust requirements mean smaller engine sizes and smaller engine weight. Less weight means more payload capacity. When all the energy produced by the engine is used for only overcoming the Aerodynamic drag force, fixed wing aircraft can get up to high cruise speeds. High speed combined with small engine power are both factors that positively affect the efficiency of the aircraft when calculating power usage over flight distance.

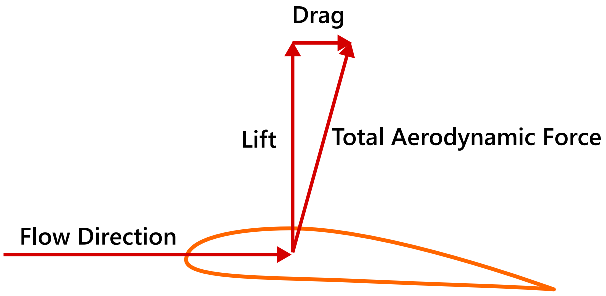

Figure 2: Airfoil Force vectors.

Positive static stability (PSS) is also one of the main benefits in fixed wing aircraft [7][8]. PSS means that the aircraft will want to correct the error that made it diverge from its original course. With Positive static stability an aircraft platform requires little active action to keep the airframe stable. All control surfaces must work against the airflow to control the airframe creating drag, by minimizing the need to use control surfaces for stable flight, means less drag and less drag means less energy used per flight distance.

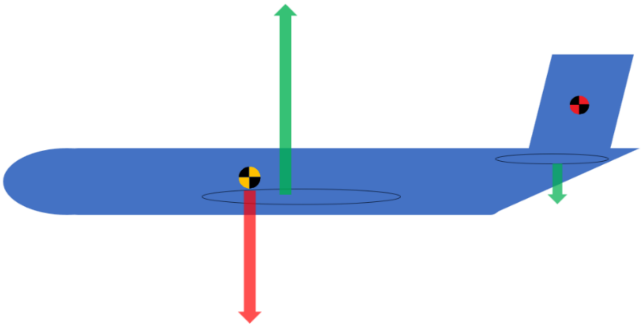

Figure 3: Lift, and gravity vectors illustrated.

The balancing forces are illustrated in Fig3, lift forces are green and gravitational force as red. By changing the ratio between green and red forces the airframe can achieve stable flight. The main force vector is the lift produced by the wings. This vector points straight upwards from the perspective of the plane and is located just behind the centre of gravity (CoG), by combining the lift and gravitational force a torque that pitches the nose of the plane down is created. This torque is counterbalanced by a force vector in the tail which creates an equilibrium. Aerodynamical force vectors are directly proportional to the speed of the aircraft. Should the speed decrease, gravity will pitch down the plane. As the plane converts altitude into airspeed, or potential energy into kinetic, the aerodynamic force vectors will get bigger, raising the nose up. The aft lift vector can be controlled in size by the horizontal stabilizer. The stabilizer has control surface which can increase or decrease the aft lift vector and thus control the pitch of the plane.

When the plane experiences lateral movement (sideslip), airflow will hit the vertical stabilizer. The airflow will now create a force vector normal to the stabilizers surface depicted in Fig 3 as red and black disc. This vector will produce a correcting torque, which will turn the airframe back into the airflow.

A dihedral angle is an angle added to the wings seen in Fig. 4 as angle α. This angle can make the plane stable in the roll axis. When the airframe experiences roll disturbance, the lift vector is not perfectly opposing gravitational forces. The green and red arrows in Fig. 4 represent lift and gravity respectively. The new sum vector (yellow) appears and causes the airframe into roll induced sideslip. The dihedral angle creates a stabilising roll torque (yellow) that corrects the roll disturbance and brings the airframe back to its stable state. The torque is created by the geometrical differences in the wings, when observing form the perspective of the airflow (Fig. 5). The wing that pierces the airflow earlier has a little bigger AoA (Angle of attack) which creates more lift as the wing has more angle to push air down. This has been illustrated in Fig 5, where right wings bottom side is visible unlike the left wings. Figures proportions enlarged for clarity. The unbalance of lift created by the wings creates the correcting torque (depicted in yellow Fig3).

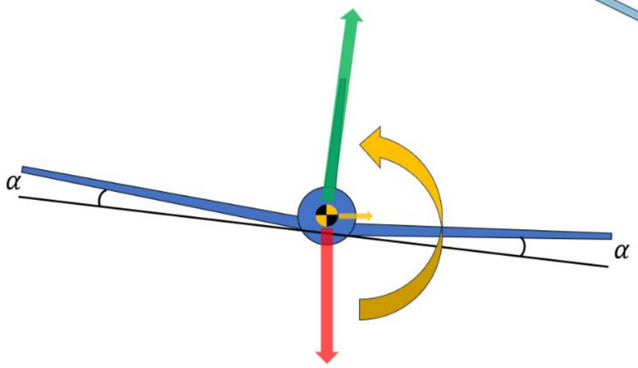

Figure 4: "Wing's dihedral angle and the correcting Roll torque"

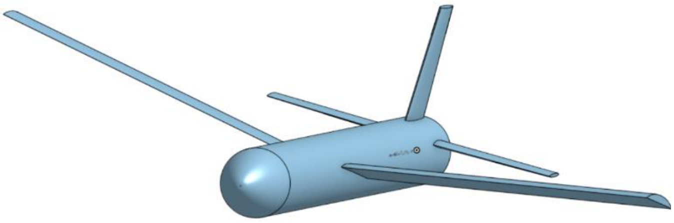

Figure 5: dihedral AoA change.

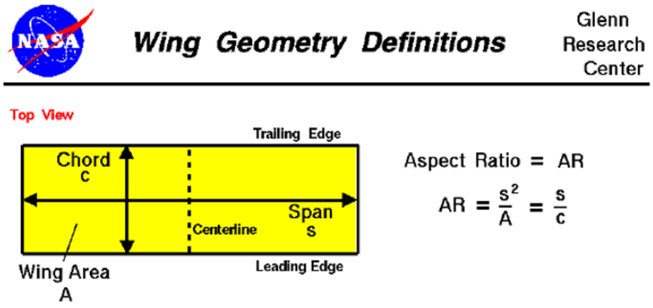

Figure 6: Wing geometry definitions

Figure 7: Sailplanes in flight

Aspect ratio is the ratio between wings Chord and its span [10]. Aspect ratio is calculated $AR = \frac{s}{c}$ as seen in figure 6. Higher aspect ratios give better flying efficiency by making use of their aerodynamic properties [11]. This can be seen in sailplanes which rely on air currents to keep them in the air (Fig 7). As these sailplanes do not have a motor to produce energy, they need to be most efficient in flight to get the best use of air currents. By having a high aspect ratio wing, they create smaller wingtip vortexes compared to their chord. By having the “same amount” of drag and bigger lift the L/D efficiency grows [11]. Wingtip vortices are induced by the pressure difference between the top and bottom of a wing (See Fig 8). The yellow arrow portrays airflow between the two pressure zones. This movement of air consumes energy that is calculated as part of the airframe drag complex.

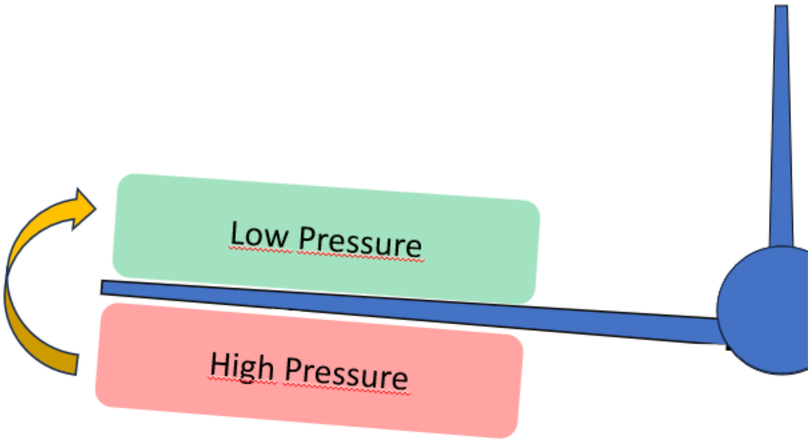

Figure 8: High- and Low-pressure zones

2.2 Rotary wing aircraft.

Rotary wing aircraft has an airframe that uses motors to rotate its wings through air. The wing surfaces experience airflow just like in a fixed wing variant when the wings is spun around a single, or multiple axis to produce constant airflow and thus constant lift. A typical helicopter is an example of single axis rotary wing aircraft which uses a rotor assembly to spin and change AoA of its rotor blades. A so called “drone” is a multiple axis rotary wing aircraft that uses fixed AoA propellers. From this point on when talking about drones their rotary wing assemblies will be referred as propellers. Unlike in fixed wing aircraft, the airframe does not require a stable airflow over its airframe to fly but generates its own airflow by spinning the rotors through the air. This means a drone can achieve stable flight while staying completely stationary. This capability is quite useful when the drone cannot use a runway to land/take off. An open space is enough for the aircraft to land and take off as it can do it vertically. This is considered to be the most important ability of rotary wing drones [12].

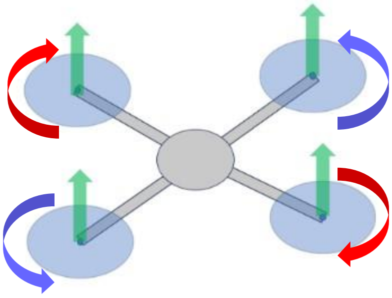

Figure 8: Quadracopter

Spinning propellers in air medium creates thrust. This thrust is generated by wings in a propeller that generate lift, much like in the fixed wing variants propulsion system. But as the thrust is the only thing keeping the drone aloft, thrust to weight ratio must always be >1. Drones control their flight by controlling their thrust vectors as seen in Figure 8. By changing the proportional size of each vector, the drone can induce torque in its airframe. This torque controls pitch and roll. By changing the direction of sum vector of thrust and gravitational force, the drone can reliably control its flight direction. When a blade spins clockwise (CW), it produces a torque in the airframe in the opposite direction, counterclockwise (CCW). This can be explained by newtons third law of motion. When two propellers spin CW and the other two CCW in a quadcopter, their created torques in the airframe cancel out. By carefully changing the rotational speed of the propellers the drone can induce a yaw torque in its airframe. This will not affect the drones pitch or roll if the spinning directions of propellers is chosen as in figure 8, because the resultant thrust vector will stay in the same place. The resultant torque, may it be in CW or CCW, will start to rotate the drone in its yaw axis.

The negative side of this airframe type compared to fixed wing is that the motors must constantly battle against gravitational forces, which consumes energy. By adding cargo to the airframe, the motors must produce more thrust in exact amount of added mass. Thus, making it not viable option for heavy carrying over long distances. Algorithms in the flight controller must be very precise and efficient for the drone to efficiently perform in turbulent, or windy conditions.

Because the drone’s airframe is not passively stable it requires active stabilisation. The drone must have high speed processing of its positional data from GPS and IMU (Inertia Measurement Unit) to precisely know its position and orientation. The flight controller must make continuous corrections for stable flight and failures of any kind endanger the drone’s operation significantly. If a single motor of a quadcopter fails, it means immediate failure of stable flight and the drone falls from the sky.

2.3 Choosing the right design

Prior to initiating the drone design process, it's essential for the designer to thoroughly consider the specific tasks the drone will need to perform. In Agriculture sector there is a demand for a drone capable of slow speeds and big lifting capabilities. Slow speed is required to ensure the right amount of spray of pesticides/seeds, or to have enough time to scan the crops. Fixed-wing design would seem to be the right choice considering the vast area. After considering other crucial parameters, rotary wing drone starts to make sense. Should the reload station be located near to the area of operation, the drone can fly back to home base to recharge and to refill the products it is spraying. Should the reload be executed quickly it would not affect the mission time significantly. By enabling frequent reloads the drone does not need to be big in size to complete its mission and carry all the required equipment. One appropriate solution to the agricultural sector is the DJI Flycart 30 [13]. The drone is specifically designed for lifting, dropping, and transporting of goods. Quick turnaround time can be seen as a centre of focus in the drone’s design. It has two batteries that can be switched efficiently, and the drone does not need to power down while the reload is in progress. The turnaround time is substantially quicker as the drone does not need to boot up and re-calibrate its sensors when it is not powered down every reload. By combining these techniques, the rotary wing drone is made a viable solution for agricultural work. While a rotary wing drone cannot fly huge distances, it can be much more efficient given the proper infrastructure to conduct a mission.

When examining some long endurance UAVs, Fixed wing variants dominate the statistics. One of the world’s best endurance drone without regenerative power source is the RQ-4 Globe-Hawk with its flight time of 30+ hour. It operates at 60,000ft and can map huge areas in a single day [14]. When inspecting the regenerative side of long endurance UAV’s Airbus Zephyr shows up as a leader in endurance [15]. The Zephyr is a unique concept, using solar panels to replenish its energy storage. By regenerating power using solar panels the Zephyr Program has managed to achieve endurance of over 14 days.

For the best flight efficiency long endurance UAV’s usually fly high in the stratosphere, from 60,000 ft and upwards. These HALE (High Altitude, Long Endurance) vehicles use the exceptional aerodynamic efficiency of the fixed wing airframe. By obtaining a high aspect ratio the drones can have extreme efficiency while soaring in lifting air currents. With big proportions the drones achieve the capabilities to facilitate enough solar panels to make power regeneration a viable option. This is why HALE platforms are usually comparable to the size of recreational aircrafts. By flying in high atmospheric conditions, these UAV’s make use of the low atmospheric pressure which reduces drag. HALE platforms, while being much cheaper, have benefits over earth orbiting satellites. They can be sent to a specific place and conduct their mission over a wanted time, while satellites are bound by their orbit paths and flyover time windows.

2.4 The hybrid approach

Some companies have produced a hybrid design. A hybrid design consists of both rotary and fixed wing features in one airframe. The Aircraft will utilise rotary wings for VTOL (Vertical Take off and Landing) and for hovering in place and use its airframe to generate lift while at cruise. This combines the wanted capabilities of both designs, but it still has drawbacks. To utilize engines in both vertical and horizontal flights the design needs either to turn its whole engine, or to have a gearbox that can transform the engines power continuously through the transition. The V-22 Osprey (see Fig.9) is a good example of an airframe that tilts its motor when transitioning between flight modes. The design choice requires more moving parts, weight, and possible weak points. A gearbox between the propeller and the engine would have the same effect.

By electrifying the propulsion, the design can eliminate the problems of redundant moving parts to a better solution. By installing many smaller electrical motors the airframe can have designated motors for VTOL flight and cruise flight. These airframes have emerged over the last years and one of them is Wing delivery drones [5]. By not relying on one motor to keep the aircraft aloft, the airframe comes with redundancy. If one motor breaks the other can take on the extra load. Furthermore, the presence of multiple motors and their associated propellers in the airstream leads to the generation of parasitic air drag. And when those motors are not used, they only create aerodynamic drag, which is wasted energy. This drag lessens the advantages of these hybrid airframe solutions. One unique solution to this is seen in the Helix eVTOL aircraft made by Pivotal Aero [16]. Here the whole airframe tilts forward when transferring into cruise flight from hover mode. By using this technique, the airframe uses all its motors the whole flight and thus does not have any unnecessary drag or weight.

Figure 9: V-22 osprey tilting motors.

3 Drone delivery

Drone delivery means in this case to deliver some cargo/goods via air route flown by an UAV. The vehicle does not necessarily need to be fully autonomous. The drone could be partially controlled by a human operator, should autonomy fail. Drone delivery is suitable for a very niche market/sector of the whole cargo delivery industry. Single drones' capacity to deliver goods is limited, which is why it needs proper infrastructure to be feasible in established cargo routes. Drones can compete with car based delivery systems by completing the A to B route quicker, as they are not affected by urban street layout, and traffic [2]. Drones average speed can be greater than a car that must obey traffic and urban road planning. As drone delivery systems advantages are tied to their superior speed and route shortening abilities, they benefit the most when delivery distances are the long, but only if the distance is still inside of the drones flying abilities. It has been examined that drones greenhouse emissions are smaller per parcel-km than ground based truck emissions [3]. A drone can be used as an airlift crane to deliver/move cumbersome material in rough or impossible terrain like jungles or mountain ranges.

3.1 Different delivery mechanisms

There are many solutions to deliver goods which can be categorised into two categories. In one method the drone flies over a drop zone, in which it drops its cargo; efficient and effective way to deliver because the drone does not need to hover in place inefficiently. With this method there is small risk for the drone to have flight affecting failures. But this method makes compromises with the possible cargo. By dropping the cargo from considerable heights, the goods need to either float down gently by minimalizing the vertical speed or be built to take a hard hit when crashing to the ground. Both methods bring extra weight and use available volume and weight limitations of the package.

By slowing down the vertical speed, with a parachute for example, the parcel has more time to be affected by wind, lowering the drop accuracy. This is an unwanted side effect and can cause the cargo to get tangled in a tree or somewhere where it would not be accessible. By making the cargo drop faster the accuracy of the drop increases, but the cargo must be sheltered from the kinematic energy at the moment of impact. Zipline is a company that makes deliveries in rural areas of Africa and has proved that dropping the cargo with a small parachute is plausible and effective [17]. Drop zones are located in fields or open spaces to ensure safe delivery.

The other method requires landing the goods down to the ground. This method is more favourable to customers, as their goods do not take damage and can be delivered with sufficient accuracy. But by using this method the UAV needs to have VTOL capabilities, or at least to be able to hover in one place. A company named WING (daughter-company of Google) uses an approach where the drone stays in the air during the delivery and it lowers the cargo using a winch [5]. This way customers are not put in danger by introducing spinning propellers with high rotational speeds anywhere near the person. By keeping the drone high WING also minimizes any noise pollution made by the drone. The box of cargo may still sway under the drone which can lead to problems. The drone has emergency system to cut the line from which the cargo is hanging from for situations when the line gets tangled or is pulled upon by malicious intentions. By cutting the line the drone is saved from possible crash and further damage to property. Zipline has come up with an idea to create a controllable container for the cargo, so it can pinpoint the drop off to a wanted spot [17]. The container has propulsion methods in all lateral axis so it can sway controllably while it is lowered to the customer. The claimed accuracy is big enough to have the cargo delivered to a doorstep.

The last method consists of landing the drone to dock, which will unload the drone automatically and convey the good to a desired destination/warehouse locker. This method requires infrastructure on both ends and would not be viable for everyday consumers. It could be used in industry logistics of a warehouse, huge factories, or some last mile delivery systems applications.

3.2 Last mile delivery system.

Like the name suggests, this topic only consist of the final step logistics of global delivery. The delivery mechanism is either to a centralized parcel locker or to doorstep delivery in suburban areas.

This type of system can compete with already established Mail truck systems in cities. Shipping over long distances in high capacity would still be dominated by Truck and Ship traffic. But there is some potential in delivering to parcel lockers. A study about parcel-lockers has proved their functionality [18]. It is possible to design those lockers to accept drone delivery methods. The technology of FMS (Flexible Manufacturing Systems) can be used to unload parcels from a drone and convey them into assigned lockers. The customer could then come and pickup their parcel form that locker at their own time. This FMS style locker could autonomously read the code of the parcel and get information from a database to execute the correct procedures for delivery. After certifying the delivery, the mailing system could send the owner a message notifying of the arrival.

3.3 Safety

When considering safety of delivery systems there are a few things to keep in mind when choosing the proper airframe and a delivering method. To minimize the possibility of damages to personnel and to property, there are some guidelines to follow. At the time of writing this thesis, EU-legislations for drone delivery systems are still in proposal phase [4]. They will be a mix of manned aviation, and specific category legislations when the proposal goes through. So this study will follow the specific category [19].

The delivery system requires autonomous flying for a drone and an operator is present only if needed. Thus, making the flight beyond visual line of sight or BVLOS which classifies as specific category. To minimize risk on cruise flight from point A to B the delivery system should implement a "Airspace corridors". These corridors would be set up in places that minimalize risks to damage of property should a failure occur [20]. The corridor would work the same way as a traditional automobile highway where drones could fly at given speeds. Because these drones fly in the same direction at the same speed mid-air collisions would be unlikely. These corridors would also have rules that regulate a proper way to merge and diverge from the lanes. Thus, giving the best throughput and safety to an airspace. These corridors would need to be setup over vacant space like fields, rivers, or rooftops of skyscrapers.

For critical failures in flight drones should have a safety parachute. The drone need to sense when to use the parachute, which could be done by monitoring different flight parameters of sensor readings [21]. The sensors will be covered later, but the parameters can be for example deviance from wanted value. If the tilt, position, speed, motor rpm etc. starts to variate too much the drone might be experiencing a mechanical or structural failure.

4 Autonomy

For an UAV to operate completely autonomously, it must be aware of its position and its surroundings. An accurate delivery system needs absolute precision to be able to deliver packages. For an automated system, which is the end goal, the drone must land precisely in its dock for loading and unloading. This chapter will start to break down autonomy into smaller parts.

4.1 Navigation

Drone gets its position with a multi-sensor system. This system gathers data from different sources and is heavily based on GPS (Global Positioning System). GPS gives helpful information about drone position which is crucial to properly navigate. Route flying is made possible by having waypoints which the drone follows. GPS alone can generate all the data the drone needs to know but cannot be relied upon solemnly. GPS tells the drone its precise Longitude, Latitude and Altitude. With addition of time the drone can calculate its speed vectors as well. By comparing the time difference between the distance of two different position measurements. In urban areas the GPS signal can bounce of obstacles such as buildings (see Fig 10), distorting the positioning calculations [22]. Because GPS relies on precise distance measurement from satellites to sensor any signal disturbance distorts the measurement. This is why the drone must use multiple sensors to provide accurate telemetry. Altitude and airspeed can be both measured with a pitot tube. Position and velocity can be double checked by a visual sensor and/or by an IMU (Inertial Measurment Unit).

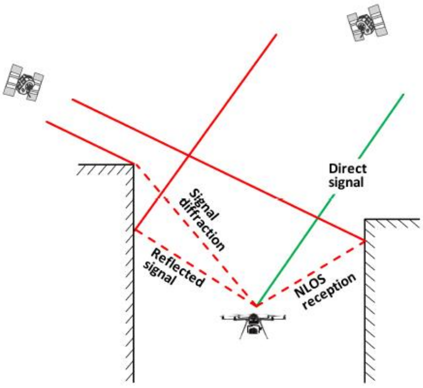

Figure 10: GPS signal interference

4.2 Obstacle avoidance

For proper obstacle avoidance, the drone must have accurate distance measuring sensors. These sensors need to be arranged in a way that they are useful for the drone’s characteristic flight profile. Cities present many obstacles in which to crash. In principle obstacle avoidance works by measuring the distance and velocity of approaching obstacles and estimate probable collisions. By knowing the obstacle distance, speed and magnitude the drone can avoid it correspondingly. With the limitations of sensors weight and volume only feasible solutions are rangefinders such as IR (infrared), radar, or ultrasound. These sensors tell the distance to the closest obstacle in their field of view but inform about safe flight path. Visual sensor such as a camera, can use sequential frames to detect how an object is behaving and conclude if it is dangerous [23]. This method is used in the commercial industry, and some high-end consumer drones have this feature. By using visual clues, the drone can determine its movement much like a human would do.

4.3 Some of the required sensors

4.3.1 GPS

GPS or Global positioning system works by calculating the distance of the sensor to a specific satellite. These satellites are part of a global constellation, where every satellite position is known extremely precisely. By calculating the distance to said satellites the sensor can triangulate its possible locations by seeing where the distances intersect. By using more satellites, the sensor can calculate its position much more precisely. Four satellites give the sensor enough data to calculate its altitude, latitude, and longitude. Every satellite sends its position and exact time when the broadcast starts. By comparing time difference the sensor can calculate how long the signal took to travel. By multiplying that time with speed of light the sensor knows its distance to the satellite [22]. By having many points in space and knowing the distance to those points, a flight computer can easily triangulate its own position on earth.

4.3.2 Pitot tube

A pitot tube uses two values of data. They are called ambient pressure and stagnation pressure. A pitot tube is a tube that is pointed straight at the oncoming airstream. At the tip of the tube airflow turns all its kinetic energy into stagnation pressure. Using advanced Bernoulli equations, the sensor can calculate the airflow velocity of the airstream by knowing both values. The sensor gets its data using a tube, that measures airflow a small distance away from the fuselage. This way it can insure that the sensor gets pure airflow. By comparing the stagnation pressure and ambient pressure the pitot tube can accurately calculate airspeed of the aircraft [24]. By using the barometric formula, the sensor can also get the altitude change made by the aircraft compared to a reference point, i.e. the take-off point.

4.3.3 IMU

The IMU or Inertia Measurement Unit is a sensor that gives data in rotation acceleration and linear acceleration, giving out Rad/s^2 and m/s^2 units respectively. By using this data and cross referencing it with itself with addition of time, a calculation of relatively accurate angular data can be done. $XAngle_{\mathrm{t}+\Delta t} = XAngle_t + (\alpha_\omega * \Delta t^2)$ where “X” represents x, y or z axis “t” denotes time at a specific moment and Δt is time difference between two different moments. Meanwhile α represents acceleration. It is important to acknowledge that acceleration values do have “noise” which are small errors in acceleration data. These errors build up as the time passes, as the angular data is calculated by iterating on itself. It is very important that when handling this kind of data that there is a setup specific filter that mathematically filters out the errors and tries to calculate accurate data. These filters work by combining angular position and gravitation direction to properly estimate the real position of the sensor. There has been a rise in Machine learning based filters [25].

5 Hypothetical delivery system

In this chapter I will create a hypothetical drone delivery system in the city of Turku, Finland. This system assumes that customer demand is infinite and thus I will design the system to cater the whole population of Turku. This system is not realistic, as there are many other factors to consider, such as customer density, financing, and infrastructure placement. Turku airport is also not considered in this exercise, as it would almost diminish the capabilities of this system. Reasoning for this is that when a proposal is passed for certified category, the delivery system could possibly be operated in the same airspace. This assumption is made because as EASA states on their website [4] the system could be designed to obey manned air traffic rules. Turku airport flight restrictions restrict any drone operations north of Turku as can been seen in Aviamaps [26]. This delivery system will be designed around drones' capabilities. This system will also be stand alone and not be relying on already established parcel shipping companies/systems such as DHL, POSTI or Post Nord. This system will serve all kinds of in City shipments. This system would be City specific, as it needs its own infrastructure relying on the topography of the city. All the Firms operating in said city could benefit from this mailing system.

5.1 System design.

This experiment will use a drone that can both hover and use its airframe to generate lift for the cruise flight phase. This airframe is explained in chapter 2.4. This design can make use of efficient and fast long-range flying and use VTOL capabilities to hand-off packages. This exercise will use WING [5] drone capabilities as a benchmark. The drone has 20km round trip range capability to carry 1.2kg of delivery mass. For visualisation of delivery range a circle can be plotted over the map of Turku with the radius of 20km (Fig 11). A single drone can deliver up to Naantali and Kaarina, the neighbouring cities. This 20km range becomes smaller when viable flight routes are factored in. Centre of the circle is positioned at one of the cities elevated locations for optimal placement in the centre of the city and for topographical elevation. Like discussed earlier this type of system requires a controlled flightpath that needs to be stationed above a scarcely populated landmass. Placing the drone hub near the river Aura will give the needed area for a controlled drone pathway. This flightpath goes through the centre of the city and there can be planned branches disengaging from it to cover the city as needed.

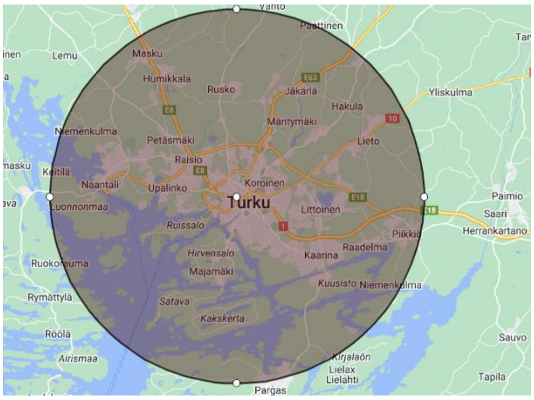

Figure 11: Drone delivery range

5.2 Package handoff

As discussed in chapter 3, there are many ways to deliver packages. In this city-wide system, it would be wise to use docking as an option, front door delivery could be implemented later. The system should be automated from handoff to delivery. A package would be placed into a sorting system, the dock would load it into a storage rack where it would wait for pickup. When the drone docks to the system, this dock would transfer the package from storage into the drone. This dock would make use of a FMS loading system, which would handle the package transporting. At the receiving end there would be same type of dock, on which the drone can unload the package. These docks can be designed in a way that they can be mounted on top of roofs, ground, or office building wall. After unloading cargo, the package would be conveyed into a similar storage rack for a human operator to pick up.

Taking inspiration from worldwide marine transport networks, these packages could be standardised. As in maritime shipping, shipping containers come in standard sizes [27]. These sizes only differ by length, while their other dimensions are the same. By implementing a rigid and light container that is in standard size, loading and unloading the drone would become easy for automation. These containers could be built from thin composite walls, which are lightweight. Standardized shipping containers would guarantee swift and easy automation on loading and unloading.

5.3 Internal mail service.

There are industries that use internal mailing. These industries include libraries, pharmacies, and big hospital campuses. Turku University Hospital is one example that consists of many different buildings that send small packages between them. After interviewing a medical student who had worked at the hospital, he said that every Monday, Wednesday, and Friday a laboratory doctor would collect laboratory samples from surrounding health clinics. The schedule of these pickups lead to unnecessary laboratory testing, so should extra laboratory work be needed, the patient would not need to wait for the next pickup. With the more frequent sample sending, the doctor would not need to take redundant laboratory samples “just in case” saving resources and time. This would also free up the schedule of a doctor to use his time better than driving around the city. These medical packages are small and lightweight, and they usually consist of laboratory experiments or pharmaceutical drugs .

Libraries rotate books between each other weekly, so that every library may have new fresh books to borrow for their local customers. After interviewing a Data analysist from Turku Main Library, it became apparent how huge the traffic between libraries is. Between the 38 libraries and deposit boxes in range of the experimental drone delivery system Turku main library sent out 155 913 deliveries in the year 2023 alone. From this it is estimated that 70% were books, so 109 000 which is still a lot of books to deliver. Vaski Libraries let their books “float” between them, so that any person wanting to borrow a book from a single library will receive it within the week to their closest library. By using the flexible method of drone deliveries, this weeklong waiting time could be cut down to hours benefiting the customer. In the year 2023 Turku Main library lend out 2.75 million books [28].

Pharmacies send out medicine and other medical supplies almost daily either as a home delivery or to nursery homes. These are scheduled deliveries of medicine refills for the elderly, according to a worker in the pharmaceutical industry. Drone delivery system shine most in unscheduled deliveries, as they are flexible systems. Adopting drone delivery into this industry could still make deliveries cheaper.

Some firms with detached office/test sites could send out small packages between their locations. When interviewing a Project and Logistics Engineer at a firm that manages project deliveries, he said that this type of flexible delivery system would benefit some firms that still use their own internal mailing service between work sites.

When considering parcel shipping, hubs may be considered at parcel shipping logistical centres in addition to the main hub of the city. From here the drone could fly straight from the logistical centre to an automated parcel locker system. This system would benefit from earlier discussed FMS technology. Packages would be stored inside the drone, after landing it would be handed to the dock where an automated system would convey the package from the drone to a locker. This way the system can implement parcel transfer in city. After interviewing some parcel locker users, it became clear that these parcel lockers can be filled to full capacity so that the customers parcel would be transferred somewhere else. This new place can be a lot farther away and be a huge inconvenience to the customer. With this drone system, a user could order their package to be delivered at a specific time such that they could pick up their parcel when the time is most convenient to them. This would free up some capacity of these lockers and better customer satisfaction.

5.4 Airspace regulations

Assuming this whole system is developed by a single firm/agency, it could be possible to implement automatic flight controller system. This automatic flight controller would consist of a computer, which monitors all flight vectors of all airborne drones. Should a probable mid-air collision situation emerge, the automatic flight controller would direct both drones to divert course. If both drones change their altitude by 10m in opposite directions, they will avoid the risk of collision and pass each other with 20m distance. In the future, when other agencies or operators would want to join the same airspace, this controlling service will be standardised. As EASA still works on regulations, an automated urban UAV flight control system will need to be created.

6 Conclusion

After conducting my research into aircraft design and the works of drones and their sensors, I have made some discoveries and come to a conclusion. Drone delivery systems are an answer to a problem that has been solved. Introducing this type of systems would need investment in money, time, and technology. Firms have minimal incentive to invest in developing such delivery systems, given the effectiveness of the existing system in place. It would be hard to compete with tested and robust technology. But the possibilities of having almost infinitely flexible quick response mailing system can bring new opportunities in service infrastructure. When small package mailing services can take up to days, this system would bring that time down considerably.

Implementing safe airspaces and permissions for drone delivery systems is a lengthy process. There is still much to consider while creating regulations. At the time of writing this thesis the European union Aviation Safety Agency (or EASA) has not decided on proper regulations for Certified category [4]. This category specifically includes drone delivery systems. The fact that these regulations are still in the proposal stage tells that drone technology is still in developing stage. The possibilities this technology gives us are still in the making and they advance at an increasing rate. As the technology advances and capabilities improve, achieving the needed precision for this type of delivery systems comes more and more a reality, but there is still a way to go. Controlled urban autonomous UAV airspace is critical infrastructure that would enable fully functional drone delivery systems. EASA should investigate in standardisation of this type of airspace and making workable regulations to facilitate UAV systems in urban areas.

My drone delivery system exercise has shown potential in small scale shipping. As I only considered the technical aspect to it, there is still much research needed to be done to fully grasp how to implement such system. The city of Turku is probably too small for an actual drone delivery system to make full benefit of its capabilities as the populus of Turku does not cover the whole capability of the system. But as I have shown in my research-based proof of concept, there is potential. Drone delivery systems show best potentials in cities with large territories, such that delivery distances are large. As distances become larger the benefits of drone delivery systems compared to a traditional mailing service also grow as talked about in chapter 3. Drones can fly considerably faster than cars, and do not get affected by traffic or road networks. The best benefit from drones is flexible and fast delivery, which is expensive to do with cars.

To summarise, Drone delivery systems have a long way to go both technologically and politically. Regulations are still to catch up with technology, and technology needs to be finetuned, but there is promise in Drone Delivery Systems from which society would benefit.

7 References

[1] A. Choi-Fitzpatrick, ‘Up in the Air: A Global Estimate of Non-Violent Drone Use 2009-2015’, University of San Diego, 2016. doi: 10.22371/08.2016.001.

[2] E. Frachtenberg, ‘Practical Drone Delivery’, *Computer*, vol. 52, no. 12, pp. 53–57, Dec. 2019, doi: 10.1109/MC.2019.2942290.

[3] J. K. Stolaroff, C. Samaras, E. R. O’Neill, A. Lubers, A. S. Mitchell, and D. Ceperley, ‘Energy use and life cycle greenhouse gas emissions of drones for commercial package delivery’, *Nat. Commun.*, vol. 9, no. 1, p. 409, Feb. 2018, doi: 10.1038/s41467-017-02411-5.

[4] ‘Certified Category - Civil Drones’, EASA. Accessed: Feb. 29, 2024. [Online]. Available: https://www.easa.europa.eu/en/domains/civil-drones-rpas/certified-category-civil-drones

[5] ‘Wing drone delivery’, Wing drone delivery. Accessed: Feb. 07, 2024. [Online]. Available: https://wing.com/

[6] P. S. Ramesh and J. V. Muruga Lal Jeyan, ‘Comparative Analysis of Fixed-Wing, Rotary-Wing and Hybrid Mini Unmanned Aircraft Systems (UAS) from the Applications Perspective’, *INCAS Bull.*, vol. 14, no. 1, pp. 137–151, Mar. 2022, doi: 10.13111/2066-8201.2022.14.1.12.

[7] ‘Lift-to-drag ratio’, *Wikipedia*. Oct. 24, 2023. Accessed: Jan. 23, 2024. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Lift-to-drag_ratio&oldid=1181606103

[8] ‘Aerobasics –An Introduction toAeronautics’. Accessed: Mar. 08, 2024. [Online]. Available: https://link-springer-com.ezproxy.utu.fi/content/pdf/10.1007/s12045-009-0102-9.pdf

[9] J. Magraner and R. Martinez-Val, ‘The birth of airplane stability theory’, *Proc. Inst. Mech. Eng. Part G J. Aerosp. Eng.*, vol. 228, no. 9, pp. 1498–1506, Jul. 2014, doi: 10.1177/0954410013494139.

[10] ‘Geometry Definitions’. Accessed: Mar. 31, 2024. [Online]. Available: https://www.grc.nasa.gov/www/k-12/VirtualAero/BottleRocket/airplane/geom.html

[11] Y. Ma and A. Elham, ‘Designing high aspect ratio wings: A review of concepts and approaches’, *Prog. Aerosp. Sci.*, vol. 145, p. 100983, Feb. 2024, doi: 10.1016/j.paerosci.2024.100983.

[12] H. Yang, Y. Lee, S.-Y. Jeon, and D. Lee, ‘Multi-rotor drone tutorial: systems, mechanics, control and state estimation’, *Intell. Serv. Robot.*, vol. 10, no. 2, pp. 79–93, Apr. 2017, doi: 10.1007/s11370-017-0224-y.

[13] ‘DJI Agriculture - Drones Better Growth, Better Life’. Accessed: Jan. 23, 2024. [Online]. Available: https://ag.dji.com/

[14] ‘Northrop Grumman RQ-4 Global Hawk’, *Wikipedia*. Jan. 06, 2024. Accessed: Jan. 24, 2024. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Northrop_Grumman_RQ-4_Global_Hawk&oldid=1194008819

[15] F. A. D’Oliveira, F. C. L. D. Melo, and T. C. Devezas, ‘High-Altitude Platforms - Present Situation and Technology Trends’, *J. Aerosp. Technol. Manag.*, vol. 8, no. 3, pp. 249–262, Aug. 2016, doi: 10.5028/jatm.v8i3.699.

[16] ‘Pivotal’, Pivotal. Accessed: Mar. 08, 2024. [Online]. Available: https://pivotal.aero

[17] ‘Zipline Drone Delivery & Logistics’, Zipline. Accessed: Feb. 07, 2024. [Online]. Available: https://www.flyzipline.com/

[18] Y. Vakulenko, D. Hellström, and K. Hjort, ‘What’s in the parcel locker? Exploring customer value in e-commerce last mile delivery’, *J. Bus. Res.*, vol. 88, pp. 421–427, Jul. 2018, doi: 10.1016/j.jbusres.2017.11.033.

[19] ‘Specific Category - Civil Drones’, EASA. Accessed: Feb. 29, 2024. [Online]. Available: https://www.easa.europa.eu/en/domains/civil-drones-rpas/specific-category-civil-drones

[20] M. Doole, J. Ellerbroek, V. L. Knoop, and J. M. Hoekstra, ‘Constrained Urban Airspace Design for Large-Scale Drone-Based Delivery Traffic’, *Aerospace*, vol. 8, no. 2, p. 38, Feb. 2021, doi: 10.3390/aerospace8020038.

[21] E. Balestrieri, P. Daponte, L. De Vito, F. Picariello, and I. Tudosa, ‘Sensors and Measurements for UAV Safety: An Overview’, *Sensors*, vol. 21, no. 24, p. 8253, Dec. 2021, doi: 10.3390/s21248253.

[22] F. Zimmermann, C. Eling, L. Klingbeil, and H. Kuhlmann, 'PRECISE POSITIONING OF UAVS – DEALING WITH CHALLENGING RTK-GPS MEASUREMENT CONDITIONS DURING AUTOMATED UAV FLIGHTS', *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.*, vol. IV-2/W3, pp. 95–102, Aug. 2017, doi: 10.5194/isprs-annals-IV-2-W3-95-2017.
[23] Y. Lu, Z. Xue, G.-S. Xia, and L. Zhang, 'A survey on vision-based UAV navigation', *Geo-Spat. Inf. Sci.*, vol. 21, no. 1, pp. 21–32, Jan. 2018, doi: 10.1080/10095020.2017.1420509.
[24] J. Pieniążek, P. Cieciński, D. Ficek, and M. Szumski, 'Dynamic Response of the Pitot Tube with Pressure Sensor', *Sensors*, vol. 23, no. 5, p. 2843, Mar. 2023, doi: 10.3390/s23052843.
[25] A. Yusefi, A. Durdu, M. F. Aslan, and C. Sungur, 'LSTM and Filter Based Comparison Analysis for Indoor Global Localization in UAVs', *IEEE Access*, vol. 9, pp. 10054–10069, 2021, doi: 10.1109/ACCESS.2021.3049896.
[26] 'Flyk'. Accessed: Mar. 26, 2024. [Online]. Available: https://flyk.com/map
[27] 'ISO-668-2020.pdf'.
[28] 'Suomen yleisten kirjastojen tilastot'. Accessed: Apr. 09, 2024. [Online]. Available: https://tilastot.kirjastot.fi/

Photos and Figures:

1. By Vector by רונאלדיניו המלך, Original by J Doug McLean - File: Airfoil lift and drag.jpg, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=77596956

6. Snippet from Nasa.gov https://www.grc.nasa.gov/www/k-12/VirtualAero/BottleRocket/airplane/geom.html

7. By CeckoNeon https://www.google.com/url?sa=i&url=https%3A%2F%2Fwww.deviantart.com%2Ftag%2Fsailplane&psig=AOvVaw011XEeIosoWWMTx2rFjRnN&ust=1711973612871000&source=images&cd=vfe&opi=89978449&ved=0CBIQjRxqFwoTCPDwnZLAnoUDFQAAAAAdAAAAABAE

9. Roy Hector Kabanlit Creative Commons https://upload.wikimedia.org/wikipedia/commons/thumb/3/33/V-22_Osprey_-_Front_View_%28Balikatan_2016%29.JPG/1024px-V-22_Osprey_-_Front_View_%28Balikatan_2016%29.JPG

10. Snippet from F. Zimmermann, C. Eling, L. Klingbeil, and H. Kuhlmann, 'PRECISE POSITIONING OF UAVS – DEALING WITH CHALLENGING RTK-GPS MEASUREMENT CONDITIONS DURING AUTOMATED UAV FLIGHTS', *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.*, vol. IV-2/W3, pp. 95–102, Aug. 2017, doi: 10.5194/isprs-annals-IV-2-W3-95-2017.