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Design of an UAV for Small Payloads Transport in Structured Industrial Environments

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Abstract

Multirotor drones have appeared as a disruptive technology with incredible untapped potential, gaining significant popularity. No accessible technology can offer the huge advantage of autonomous flight with hovering capabilities brought by multirotor drones. This simple yet powerful ability opens doors in an enormous amount of industries, such as photography and videography, where the aerial point of view used to be reserved for some but is now available to most; for farming, where multiple sensors can be implemented for crop monitoring, or used for seeding and fertilizing; for general surveying, such as construction sites or hard-to-reach places; used in all types of search and rescue missions where eyes on the sky can mean the difference between success and failure; and many, many others.

In this dissertation, a cargo drone prototype is developed to carry a one-kilogram payload safely. The document reports knowledge about the individual parts of a drone, their purpose and how to assemble, configure and operate them.

One key focus of this dissertation is the software used for controlling the drone, *Ardupilot*. With *Mission Planner*, the personal computer software pair of *Ardupilot*, many of the software's features were explored to achieve the set goals. Some of the components, such as the controller, GPS and compasses, were calibrated using this software, as well as the required configurations to fly and operate the drone correctly. Testing was done recurring directly or indirectly to this software, using the included part tests and by flying the craft itself.

Resumo

Os drones multirotores são uma tecnologia disruptiva com um incrível potencial inexplorado, tendo recentemente ganho popularidade significativa. A enorme vantagem do voo autónomo com a capacidade de pairar trazida pelos drones multirotor demonstra a singularidade da tecnologia. Esta capacidade simples, mas poderosa, abre caminho para uma enorme quantidade de indústrias, como a fotografia e a filmagem, onde o ponto de vista aéreo era difícil de obter previamente, mas agora é facilmente acessível para a maioria; para a agricultura, onde vários sensores podem ser implementados para monitorizar as colheitas, ou usados para semear e fertilizar; para inspecionamento em sítios de construção ou locais de difícil acesso; usado em todos os tipos de missões de busca e salvamento, onde visão aérea pode significar a diferença entre o sucesso e o fracasso; e muitos, muitos outros.

Nesta dissertação, é desenvolvido um protótipo de um drone para transportar um quilograma de carga em segurança. O documento apresenta o conhecimento sobre as partes individuais de um drone, a sua finalidade e a forma de as integrar, configurar e operar.

Um dos pontos principais focados nesta dissertação é o software utilizado para controlar o drone, o *Ardupilot*. Com o *Mission Planner*, o par de software para computador pessoal do *Ardupilot*, foram exploradas muitas das funcionalidades do software para atingir os objetivos definidos. Alguns dos componentes, como o controlador e o GPS, foram calibrados através deste software, tal como foram feitas as configurações necessárias para o drone voar e operar corretamente. Os testes foram feitos recorrendo direta ou indiretamente a este software, utilizando os testes incluídos e voando a própria aeronave.

Reconhecimentos

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Durante a pandemia da COVID-19 foi quando compreendi o valor que os amigos têm. “Só se dá valor quando se perde”; todos as minhas amizades foram condicionadas aos ecrãs durante tempo a mais. Hoje não tenho prazer maior do que estar com vocês, amigos.

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João Rosendo

“You either get bitter, or you get better. It’s that simple. You either take what has been dealt to you and allow it to make you a better person, or you allow it to tear you down. The choice does not belong to fate; it belongs to you.”

Josh Shipp

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Abreviaturas e Símbolos

UAV	Unmanned Aerial Vehicle
Kv	Brushless Motor Velocity Constant
GPS	Global Positioning System
BLDC	Brushless direct Current Motor
IMU	Inertial Measurement Unit
PID	Proportional-Integral-Derivative
VTOL	Vertical Take-off and Landing
ROS	Robot Operating System
PLA	Polylactic Acid

Chapter 1

Introduction

Multirotor drones are a type of unmanned aerial vehicle (UAV) propelled by two or more independent motors that generate lift, even though most have at least four [16]. These motors are individually controlled by a processor running control software and energized by a battery in the drone body. Moving and changing direction are done by giving more power to certain motors and less to others: this tilts the drone, and because of this tilt, it moves in this direction.

Because of their versatility, affordability, and simplicity, drones are being used in a wide range of applications. They're commonly bought for entertainment, whether it be as small toys for children or as extremely fast racing drones; used for photography and videography because of their flight capabilities and advantageous point of view; used in farming paired with various sensors for crop monitoring or for seeding and fertilizing; used for surveying construction sites and already constructed infrastructure for potential problems; used in search and rescue operations for helping locate missing people and assist in emergencies or in law enforcement, and many other use cases.

1.1 Context

It was in 1783 that man conquered the dream of gaining wings. This year represents the date of the first manned flight; however, the fight did not end there. Ever since, research about flying vehicles has been constant and intense. More recently, with the evolution of wireless communications came the possibility of autonomous controlled flight. Ingenuity is a robotic helicopter that landed on Mars in 2021, programmed to be automatically controlled and with a wireless connection established to Earth, sending back information and photographs. Multirotor drones are an upcoming technology with huge potential across various industries. Their simplicity, combined with flight and hovering capabilities, make a compelling package that can be applied in many fields, such as photography and videography, where the aerial point of view used to be reserved for some but is now available to most; for farming, where multiple sensors can be implemented for crop monitoring, or used for seeding and fertilizing; for general surveying, such as construction sites or hard-to-reach places; used in all types of search and rescue missions where eyes on the sky can mean the difference between success and failure; and many, many others.

This project is part of "Project GreenAuto: Green Innovation for the Automotive Industry", with the objective of researching and implementing automatization in industrial applications.

1.2 Motivation

In recent years, multirotor drones have emerged as a disruptive technology with transformative potential across various domains. These flying vehicles have a wide range of real and potential applications, helping fill many shortcomings in different industries by bringing flying and hovering capabilities to the table.

More specifically, cargo drones have a high potential for carrying small to medium payloads indoors, as they move rapidly and can avoid congested spaces when compared to ground transport, and have the potential of being automated, reducing human intervention to a minimum, which not only enhances operational efficiency but also reduces the risk of human error.

The worldwide commercial drone market was estimated at around twenty billion dollars in 2022 and is expected to grow at a compound annual growth rate of about 14% from 2023 to 2030 [17]; It is clear that this is a very rapidly growing market with a huge potential for applications that are yet to be implemented.

All-in-all, drones have demonstrated remarkable potential in various fields. The increasing adoption of drones across industries reflects the recognition of their value, further proven by its constantly growing and predicted-to-grow-more market.

1.3 Goals

The main objective of this dissertation is the complete development of a cargo drone capable of flying while carrying at least one kilogram of weight.

To complete this objective, one must know and fully understand the components required to create a drone, which will require thorough bibliographic research, reading component documentation and partaking in communal discussion boards. This knowledge will be necessary throughout the part-choosing, assembly and testing process.

Choosing the correct and best-in-class parts is important for maximizing drone performance; this must be done through thorough market research. The resulting performance will depend mostly on this part of the work. The assembly and configuration must be done carefully not to damage any component in the process and guarantee safety. The build's reliability and security will be very dependent on this part. Testing has to be done under safety guidelines for operating drones and with the proper sensibleness in mind.

Chapter 2

Background and State of the art

2.1 Background

This section will serve as an introduction to the multirotor drone, how they operate, their most common variants, and their various components. This is the necessary background information required to understand why and how drones exist, and what components and software are required to run one.

2.1.1 Operating Principle

Multirotor drones are simple in nature; they have all of their motors pointed upwards; these motors have propellers attached to them, rotating them. These propellers are the sole generators of lift. If all propellers rotate at a high enough speed, they will generate enough thrust to surpass the gravitational pull of the earth, making the drone take off and fly. Because of the torque effect caused by the propellers spinning, if all propellers spun in the same direction, the drone body would tend to revolve around its centre, making stable flight difficult. To avoid this effect, half of the propellers rotate clockwise, and the other half rotates counterclockwise, effectively cancelling rotational forces. The flight controller plays a crucial role in flying the drone. It adjusts the speed of each motor and propeller independently to control the drone's orientation, stability, and movement in different directions. By adjusting the rotational speeds of the propellers, the flight controller can maintain a desired attitude and manoeuvre the drone as commanded by the pilot or autopilot.

2.1.2 Drone Body

Figure 2.1: Example of a drone frame. [1]

Drones generally have a symmetrical appearance, featuring a central area that typically houses components like the controller, battery, and other peripherals. This central space can either be open or enclosed to ensure protection and optimize aerodynamics. An example of a drone body without components installed can be seen in 2.1.

Because of the symmetry, the centre of gravity aligns with the visual centre, making it the ideal point to attach any heavier components or a payload, such as batteries, cameras, or cargo. It is worth noting that ideally, the components should balance out with each other so that after they are all added, the centre of gravity still aligns with the symmetric centre.

The drone's arms extend outward from the central area. It's common for the arms to be tube-shaped, but there are several varieties of arms designs. Cables run through or around the arms to the motors, which are attached to platforms at the end of the arms. Some drones have protections around the propellers to create a barrier between anything the propellers might otherwise come in contact with. Some drones have foldable arms and propellers to make transportation easier.

Landing gear will be present on most models, as it helps reduce the probability of damage when landing, can protect the drone body in case of an accident, provides a stable platform for the drone to sit on, and can give clearance for the propellers when close to the ground. It also prevents the drone body from becoming dirty or coming in contact with harmful substances. Furthermore, some drones can have peripherals or cargo on their bottom (belly), so landing gear helps avoid unwanted contact in these cases.

2.1.3 Drone Piloting

Drones can be piloted by a human operator remotely. Using a radio control (RC) remote controller and receiver, they can be flown by line of sight, where the operator can directly see the drone and consequently fly it in a way that avoids obstacles; or they can be flown with first-person view (FPV), which requires a camera attached to the drone body. The operator can look at a screen receiving the live camera feed, which shows the drone's point of view, and consequently avoid any obstacles. Drones can also be piloted automatically through autopilot software, taking in information from several sensors and using the global positioning system (GPS). [18]

Because of the non-linear nature of a drone's dynamics, they require some loop control to stabilize the vehicle. As an example, a drone that is currently in the air, and is receiving no movement input, should control its motors in a way that stabilizes it in a still position, generating enough lift in each motor to counter the force of gravity and choosing which motors should receive more thrust to counter the wind if there is any.

2.1.4 Drone Configurations

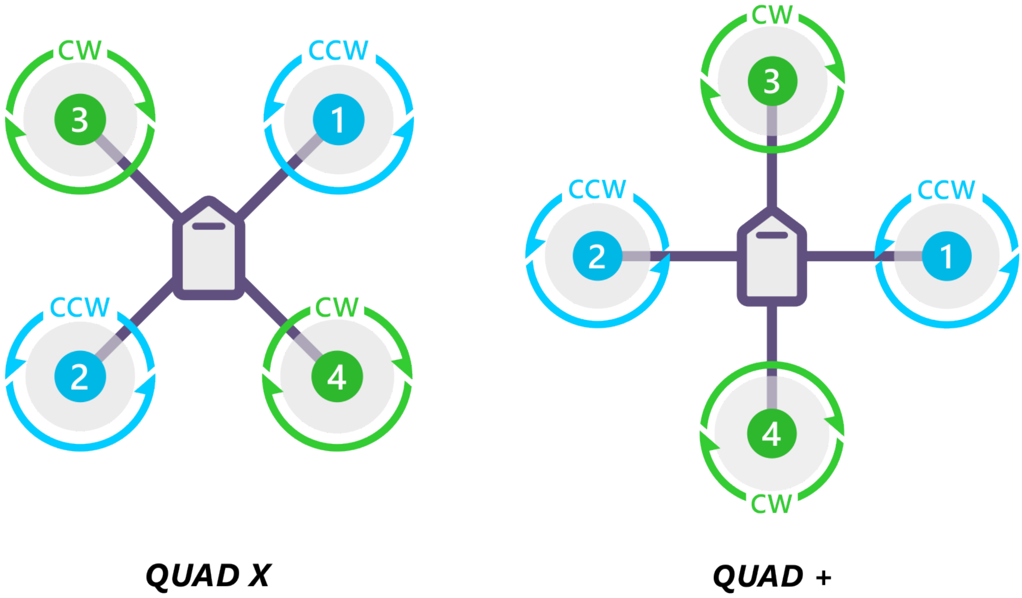
Multirotor drones have several configurations. The most common is the quadcopter configuration, often seen in the consumer market as recreational drones. Hexacopter or octocopter configurations offer more lift when compared with a quadcopter with the same motor type. Because more motors are used, they are more expensive when compared to the quadcopter and empty the battery more rapidly. These configurations are often seen in the cargo drone market since they are more powerful and thus can carry more weight. A common use for such drones is photography and filming with professional cameras, which are usually heavy compared to FPV cameras. For reference, the weight of a DSLR camera with a lens starts in the order of 1000 grams, while the weight of an FPV camera starts in the order of 10 grams. It is also worth noting that hexacopters and octocopters can still operate with failed motors, even though not at total capacity [19, 14]. This is safer for the drone and any carried cargo because the motors can, in some cases, be used to slow the fall of the drone in a controlled way. While quadcopters and hexacopters always have one motor per arm, it is possible to find octocopters with four arms and two motors per arm, essentially looking like a quadcopter.

2.1.4.1 Quadcopters

Quadcopters can be configured in two main ways: the "cross" configuration and the "plus" configuration. These configurations refer to the arrangement of the drone's four arms in relation to the body frame axes.

In the "cross" configuration, the drone's arms are positioned at a 45-degree angle from the body frame axes. This means that when viewed from above, the arms form an "X" shape. The opposing motors in this configuration rotate in the same direction.

On the other hand, in the "plus" configuration, the drone's arms are aligned with the body frame axes. When viewed from above, the arms form a "+" shape. Similarly to the "cross" configuration, the opposing arms in the "plus" configuration also rotate in the same direction.



(a) Cross configuration quadcopter.

(b) Plus configuration quadcopter.

Figure 2.2: Standard quadcopter configurations. [2]

The cross configuration is usually preferred for several reasons:

The first advantage of the cross configuration is that the front of the drone is unobstructed, which is very advantageous for drones with mounted cameras since they're usually pointing forward.

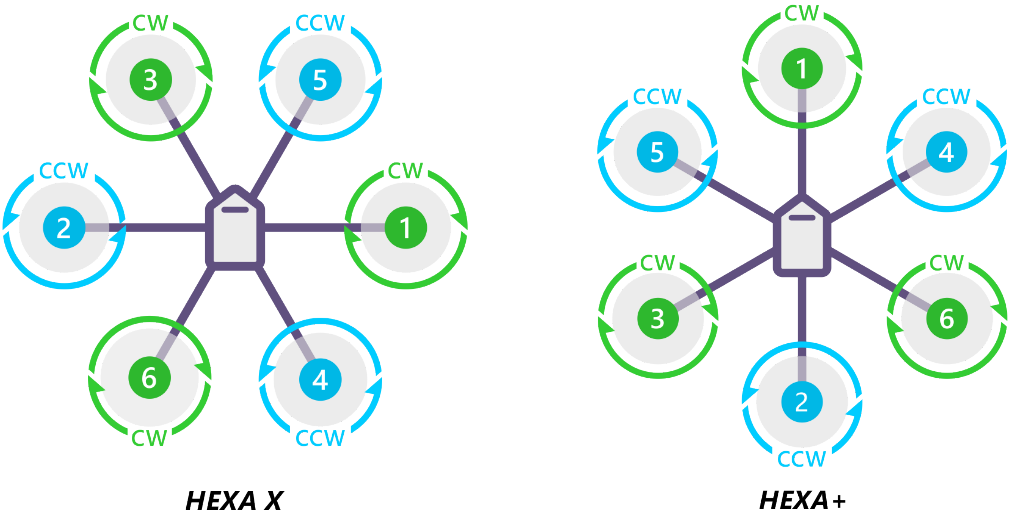
The second advantage is that each side has counter-rotating propellers, which cancel each other out in case of the drone pitching or rolling. This is not the case in the plus configuration, which makes control more difficult and unpredictable. [20]

The third advantage is that when pitching or rolling, the thrust comes from four motors at the same time instead of just two. For example, pitching forward in a cross-type quadcopter would be done by supplying motors two and four more power and reducing the power of motors three and one, which would result in an angular movement around the drone's centre of mass, making the drone point its front down to the ground. In the plus-type quadcopter, a similar process happens; however, because there are only two motors capable of exerting force to pitch the drone, the movement is slower. Furthermore, unlike the cross-type quadcopter, the motors do not cancel their torques, and because of this, the drone will always yaw a small amount when performing this operation.

We know that $\tau = r * F * \sin(\theta)$ with r being the radius, F the force exerted by one motor, and θ the angle between F and the lever arm. For the plus type quadcopter, taking into account the pitching forward example and considering only the motors which gain thrust, we have $\tau_1 = r_1 * F_1 *$

$\sin(\theta)$ since only one motor is gaining thrust. However, for a cross-type quadcopter, the resulting force comes from two motors, so we have $F_2 = 2 * F_1$. Because of the resulting torque being applied in the centre between the two motors, the resulting radius is $r_2 = r_1 * \cos(\pi/4)$. Finally, we have $\tau_2 = r_1 * \cos(\pi/4) * 2 * F_1 * \sin(\theta)$ which is roughly equal to $\tau_2 \approx 1.414 * r_1 * \sin(\theta)$. From this, we can conclude that the cross configuration has roughly 41% more thrust in this situation than the plus configuration. [20]

2.1.4.2 Hexacopters



(a) Cross configuration hexacopter.

(b) Plus configuration hexacopter.

Figure 2.3: Standard hexacopter configurations. [2]

Hexacopters, similarly to quadcopters, usually come in the "cross" or "plus" configuration. The difference between both is that in the "cross" configuration, the drone arms are at a 30º angle from the body frame axes, while in the "plus" configuration, they are aligned.

Hexacopters have more redundancy when compared to quadcopters; With six propellers, the drone can always continue being controlled if one motor fails, and in some cases of two or three motor failure [14]. This redundancy enhances the overall stability and safety of the aircraft and is the best quality of the hexacopter.

Compared to a quadcopter with the same motors, a hexacopter will have more lifting power, allowing it to carry heavier cameras, batteries, or cargo. Hexacopters are more suitable for carrying cargo than quadcopters.

Because of the higher number of motors, hexacopters will inherently consume more battery charge than an equivalent motor quadcopter, which can be offset by including bigger batteries, which the hexacopter should be able to carry.

Both hexacopter frames have counter-rotating propellers, which cancel each other out in case of drone pitching or rolling. It is a matter of preference or availability on which frame type to pick.

2.1.5 Drone Components

A multirotor drone is made of several standalone parts. These will be explored in the following subsections.

2.1.5.1 Frame

The frame is the skeleton to which every component will be attached. It must be very sturdy to avoid being damaged easily and to avoid vibrations caused by the motors, making it harder to control. It should be as light and as aerodynamic as possible. A frame with good mounting points and good accessibility is very advantageous for saving time in building and modifying. The choice of material is vital because it directly influences both the weight and rigidity of the frame. Carbon fibre is a popular choice due to its excellent strength-to-weight ratio, making it strong and lightweight. The size of the drone is also important to take into consideration. It should be as big as required, but not bigger than that, as that would mean excess weight. Frames are designed around the propeller size; This means the recommended propeller for them is usually as wide as they be without hitting each other.

2.1.5.2 Propellers

The propellers are responsible for generating lift, and choosing the appropriate propeller is very important because they determine the drone's performance and efficiency. Propellers come in two types of rotation: Clockwise and counterclockwise. This is due to the fact that half of a drone's motors run in the clockwise direction and the other half in the counterclockwise, so the propellers must be sold in both configurations too. Propellers have an associated number which describes them: For example, a "5x4.5x3" propeller has a five-inch diameter, a pitch of four and a half inches, and three blades. The pitch is a measure of how much the propeller would move forward in a full rotation, in a solid and without drag. [21] A drone must have the right size propeller for its motors. Motor manufacturers usually recommend propeller sizes to pair with each motor they produce. The material is also essential since propellers must be very sturdy, so they don't distort with speed changes, and very light, so they don't affect the motor angular acceleration too much. Again, carbon fibre is often used for its high strength-to-weight ratio. Drone propellers usually have either two blades or three blades. Two blades are more efficient and make less noise than other types, but propellers with three blades are able to generate more power when compared to a two-bladed propeller of the same size. Propellers are very dangerous when rotating because they have very high angular speed, spinning at rotations per minute (RPM) in the order of the 1000s. Because of this and their material, they can easily cause damage when touching anything. A propeller is expected to not touch anything except the air while rotating because it can also easily damage itself.

2.1.5.3 Motors

Motors are what make the propellers rotate. Drone motors are brushless, direct current motors (BLDC). These motors are ideal for drones because they are best for high speeds where continuous rotation is needed [22]. BLDC motors are essentially very small three-phase motors, taking three-phase current for power. Compared to a brushed motor of the same size, brushless generate more power, are more efficient, have a longer lifespan, are quieter, and have better control capabilities. However, they require a dedicated controller per motor. These controllers are called Electronic Speed Controllers (ESCs). The main benefits of BLDC align with what is expected of a drone motor. However, it's worth noting that motors are usually not expected to run at full power for long periods. On the contrary, motors have a recommended thrust to operate at. This value varies but usually is around 50%. Beyond this percentage, the motors can operate for a certain time before risking permanent damage due to excessive heat. Furthermore, motors are often more efficient when running at lower speeds. Finally, it's necessary to have some thrust in reserve for emergencies such as an unseen obstacle or motor failure.

2.1.5.4 Electronic Speed Controllers

Electronic Speed Controllers are essential for motor control. Essentially, an ESC is an inverter, converting direct current to alternating current. It outputs three alternating currents, shifted by 120 degrees from each other. They are connected by a three-wire cable to the flight controller and receive an input PWM signal from which it interprets the desired speed for the motor. With this target, they regulate the current delivered to the motor and thus its speed. ESCs can have a lot of current flowing through them: one manufacturer produces ESCs capable of delivering up to 200A continuously. Because of this, they usually have some heatsink to dissipate any excess heat from power losses, and can weigh a significant amount. Two cables run from the power distribuition board to the the ESC, supplying it with power. Three output cables connect to the motor.

2.1.5.5 Battery

The battery is the source of energy in the drone. It must be as light as possible and have a high energy density while being able to discharge very fast. There are many available batteries with different characteristics. The battery can't be too heavy compared to the drone's total weight, but it must have enough capacity for the required flight time. The battery must have a high discharge rate to provide enough current for all motors. The battery's discharge rate should be at least as high as the consumption of all motors at max thrust. The best batteries widely available in the market are Lithium Polymer (LiPo) batteries. [23] Most drones use LiPo batteries because of their superior characteristics, such as high energy density and discharge rate.

2.1.5.6 Flight Controller

The flight controller is the main computer of a drone. It's responsible for controlling the drone's movement and stability. Every component will be connected to the flight controller in some way. There is a wide range of drone controllers in the market. Some are very simple and inexpensive, while others offer many features and are very expensive. Different flight controllers can have different microcontrollers. These microcontrollers vary in processing power and firmware and, therefore, can change the drone's controlling attitude. Some flight controllers have more and better positioning sensors than others (gyroscopes, accelerometers, barometers). These positioning sensors are often packaged into units called inertial measurement units (IMU), which are important for the aircraft's stabilization, orientation and motion. The communication protocols vary among available options (I2C, UART, SBUS, PWM, PMU, etc.). Even though they're usually small and light, their size and weight vary, which can be relevant in smaller-sized drones. It is worth noting some flight controllers aimed at smaller drones come with included ESCs, often coming as two electronic boards stacked on top of each other.

2.1.5.7 GPS

The Global Positioning System, also known as GPS, is critical for UAVs that fly outside of buildings, as it enables them to determine their precise location. A GPS receiver works by receiving signals from multiple satellites, which means a UAV can triangulate its position. This permits it to maintain a stable hover and follow a pre-programmed flight path, such as flying to several waypoints set by an operator. It can also be used for a "Return-to-Home" function which automatically flies the drone back to its takeoff point, a function can safeguard the drone in case of loss of remote control connection. Precise position hold, geofencing and photography geotagging are other use cases for GPS in UAVs. The GPS module should be positioned in an unobstructed place, far away from other noise-emitting components, as they can reduce the effectiveness of triangulation. Even still, some outdoor places might have limited or no GPS connection because of natural and human-made obstacles. UAVs in indoor places will most likely get no GPS triangulation.

2.1.6 Cargo Drone Use cases

Cargo drones are a type of specialized drone to carry goods aerially. They are usually bigger and more potent than FPV drones because they must make enough thrust to move themselves and their cargo. This means that their components are generally heavier, more potent, and more expensive. Because the motors must have enough power to carry the required cargo and still operate at their recommended thrust, motors and ESCs are very powerful and consume a lot of power. Cargo drones can be used to transport payloads from one place to another. Amazon Prime Air is Amazon's delivery service for transporting packages directly to customers using cargo drones. They can also transport urgently needed medicine, like the company Zipline does, using winged UAVs. The use of delivery drones in healthcare can revolutionize the way medical supplies and equipment are delivered to patients, especially in hard-to-reach places. Some places might take days for a human to reach and deliver, while a flying drone can simply ignore terrain and fly almost in a straight line. This can help to improve access to healthcare for people living in these areas and reduce the burden on healthcare systems. Another potential application of delivery drones in healthcare is the transportation of medical samples, such as blood or tissue samples, for laboratory analysis, which can speed up the diagnostic process, especially in urgent situations. Photography (or filming) drones can be considered cargo drones. Cameras can be regarded as a payload since they are quite heavy compared to a drone's total weight. Cargo drones can be used in agriculture: They have proven to be powerful for farmers, providing them with information about the health and growth of their crops, as well as the ability to perform tasks like spreading seeds (seeding) and fertilizer. T more efficiently and effectively than the traditional farming methods, leading to cost reductions and/or bigger yields.

2.1.7 Drone Control

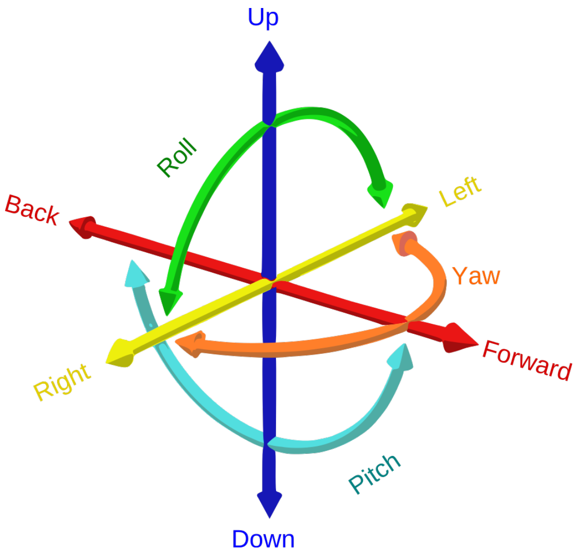


Figure 2.4: The six degrees of freedom. [3]

Drones have 6 degrees of freedom (up/down, left/right, forward/back, roll, pitch, and yaw, which can be seen in 2.4). These are all the linear and angular movements that exist, meaning they can move in any way possible, as opposed to, for example, a train, which is limited to one degree of freedom by its tracks.

Even though drones are submitted to 6 degrees of freedom, they only have motors on the up/down axis. This makes them inherently unstable and hard to control directly, so some type of processing and digital controlling is required so that movement can be predictable and safe. Because of the drone's structure, four basic movements are used to piece together a moveable drone: Throttle, roll, pitch, and yaw. [24]

As an example, When the drone performs a pitch or roll, assuming it was previously hovering, the vehicle will suffer a slight tilt in a given direction, and consequently, the propellers will also tilt in this direction. This means the propellers are no longer perpendicular to the force of gravity, with the resulting force moving the drone horizontally while also holding it up against gravity. This simple manoeuvre requires internal control, as it is inherently unstable. When the drone does the pitch or roll, the tendency would be for the manoeuvre to keep going because of inertia, but only a slight angle is wished, or the drone would very quickly lose stability. The controller must counter this inertia and stabilize the manoeuvre. It must also predict the reduction of the force component that is fighting gravity and respectively compensate for this reduction, or else the drone would lose altitude.

The included inertial measurement units in the flight controller are key for this control. These sensors continuously measure the drone's linear acceleration and angular velocity, giving the necessary measurements for controlling these attitudes. Proportional-Integral-Derivative (PID) control loops are fundamental algorithms used by flight controllers to stabilize the drone. The control loops take the information from the inertial measurement units, comparing the desired orientation with the actual state. Based on the difference between these values (error), the controller calculates proportional, integral, and derivative values and adjusts the motor outputs, keeping it stable and following the predicted attitude.

2.2 State of the art

This chapter will be used for discussing the current state of the art relating to drones, their construction, control, use cases, and several implementations.

2.2.1 UAV description

The authors of [18] stated that unmanned aerial vehicle (UAV) refers to a controlled aerial vehicle that doesn't carry a human pilot inside it, but instead is remotely controlled by an operator or automatically controlled by an autopilot. The term "UAV" and "drone" are often used interchangeably.

Because of their flying capabilities, advantageous positioning, good stability, and high endurance, UAVs are used in various civilian and military applications. Throughout the years, the applications of such vehicles have been growing in "object detection and tracking, public security, traffic surveillance, military operations, exploration of hidden or hazardous areas, indoor or outdoor navigation, atmospheric sensing, post-disaster operations, healthcare, data sharing, infrastructure management, emergency and crisis management, freight transportation, wildfire monitoring, and logistics ". Their remote and autonomous capabilities allow for more cost-efficient operations and remove the factor of putting human life at risk.

Nonetheless, there are many shortcomings that limit UAVs' capabilities. In terms of technology, a UAV can only function as long as it has a battery charge, and because bigger batteries are heavier, more power will be consumed. Batteries are not very energy dense compared to UAVs' energy consumption, resulting in little air time. Harsh weather is dangerous for UAVs because they are susceptible to water damage and can easily be blown toward unwanted places by strong winds. Because of UAVs' wireless capabilities, they are susceptible to malicious attacks.

UAVs are available in many configurations. Size can vary from very small (the size of a finger) up to very large (the size of a combat jet); power can come from batteries or combustion; lift can come from wings (Fixed-wing aircraft) or directly from propellers (Rotary-wing aircraft); communication can be in between short or extremely long range; propeller number varies from 1 to more than 16. The equipment also varies widely: Cameras, GPS, sensors, gimbals, batteries, frames, and controllers vary depending on the size and desired application.

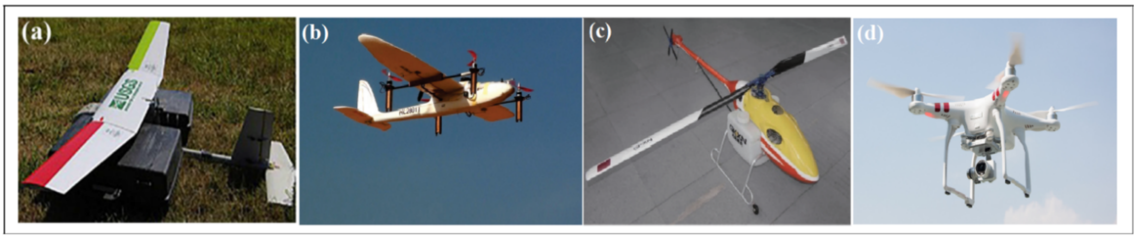


Figure 2.5: (a) fixed-wing, (b) fixed-wing hybrid, (c) single rotor, and (d) multirotor UAV. [4]

In figure 2.5 we can see different configurations of UAVs. Fixed-wing aircraft use the wings to generate lift. Instead of being the generators of lift, the propellers generate forward motion. The wings are designed to make air move faster over the wing, decreasing the pressure in the top part. This pressure difference creates a force that moves the aircraft upwards[4]. Fixed-wing aircraft are efficient but require a minimum speed so they don't stall, meaning they cannot hover like rotary-wing aircraft. Changing direction takes more time than rotary-wing aircraft. They also need a runaway to take off and land, limiting their reach to places with one.

In a rotary-wing aircraft, all propellers rotate pointing straight up and generate all the lift this way, meaning the vehicle is capable of vertical takeoff and landing (VTOL); hence, a runaway is not necessary for launching and landing. Hovering is also possible and is one of the main benefits of rotary-wing aircraft. They can easily change direction and altitude. Generally, they're considered more versatile because of these capabilities, but also less energetically efficient[24].

2.2.2 UAV use in factories

Indoor application of drones is much less common because of the higher amounts of obstacles and the impossibility of using GPS. The risk of humans and assets being harmed is also higher. The authors of [5] stated that "High potential was found in using drones in routine inspections of thermal losses in injection molding machines, which would normally require manual inspection. However, with piloted drones, the return on investment would be marginal because a human operator would still be needed. It was concluded that the use case is viable, but only with automated drones." It can be said that drones can fill certain niches inside factories if enough advancements are made permitting safe and efficient automation. In the same article, the challenges of partially automating drones for the above-referred task are examined. For this examination, part of a real factory was ported into a virtual simulator (Gazebo). Using robot operating system (ROS), which is "a set of software libraries and tools that help you build robot applications"[25], a drone body was inserted into the simulation.

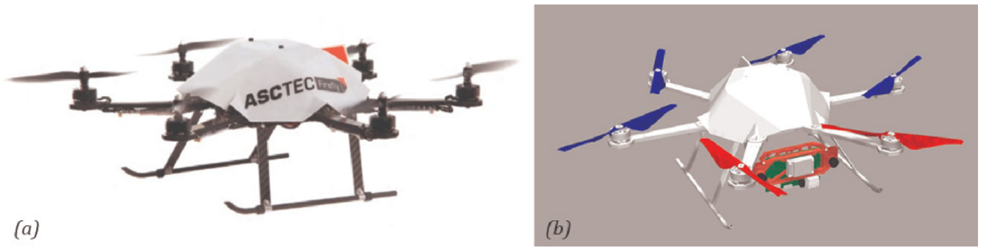


Figure 2.6: (a) Real AscTec Firefly drone; (b) Simulated Firefly hex-rotor drone in Gazebo.[5]

The real and simulated drone can be seen in figure 2.6; it can be seen that they are similar in appearance. The simulated drone has sensors like a real one does: an inertial measurement unit, an odometry sensor, and others. A controller is also part of the drone, allowing for high-level commands such as path planning and collision avoidance, which permits automation, the main objective. The factory floor was analyzed, and the permitted airspace was defined, including a take-off and landing area. Two flight scenarios with predefined waypoints were created for the drone to follow and inspect thermal losses in injection molding machines: a "quick and limited" run and a "slow and detailed" run. After running the simulation, it was noted that each quick run took 3 minutes and 52 seconds and that each slow run took 5 minutes and 47 seconds, compared to an estimated 90 minutes per manual run. This shows a significant improvement, especially when taking into account that the manual run requires a worker but the drone can be automatized. Since the drone runs are quicker, they imply an earlier detection of irregularities in the machines, resulting in higher efficiency.

2.2.3 UAV propeller cage

If drones are to be adopted for widespread use, safety is a must. Depending on the implementation, unprotected propellers can be dangerous, whether it be to people or to structures.

The writers of [6] implemented a protective and foldable cage around an entire quadcopter, which is also capable of carrying cargo. The authors stated that even though some over-the-Counter drones have protective plastic elements, they may not be enough as they only protect propeller contact from the sides; and that a safer approach would be to enclose the drone completely. This way, the components of the drone are safe from damage by impact, and any object is safe from propeller contact. The design permits a person to catch an approaching drone simply; or for the drone to safely land in emergency situations where there is no ideal place for landing. One of the main concerns of implementing a full cage is its big size, as it results in difficult transportation. Because of this, the authors decided a foldable cage would be beneficial and desired to eliminate this concern.

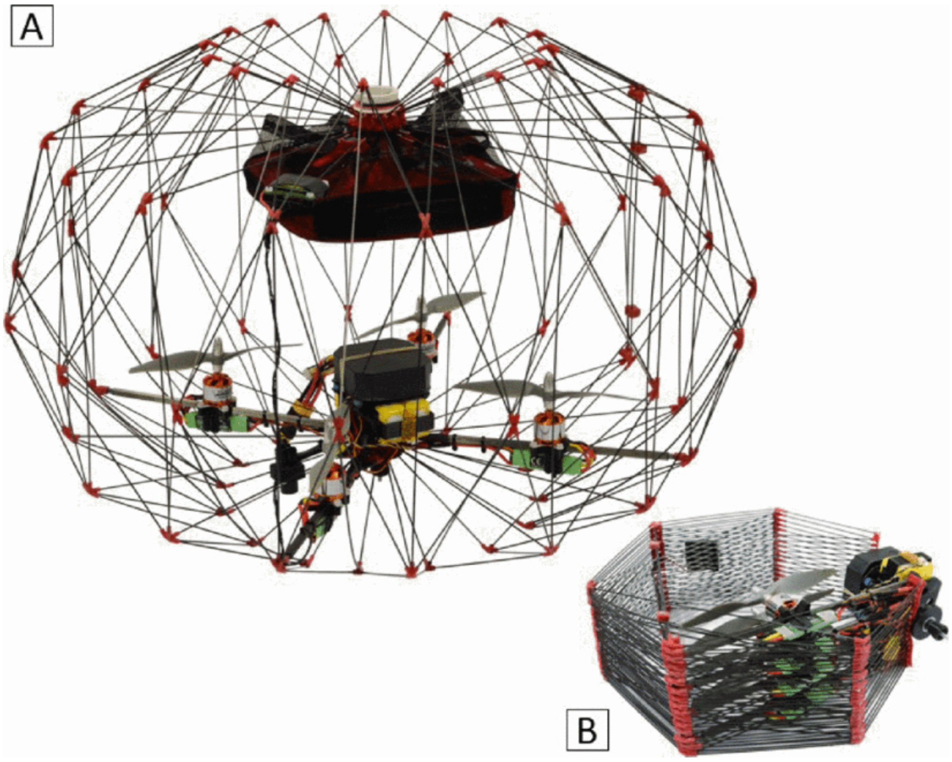


Figure 2.7: The foldable cage drone prototype, respectively opened and folded.[6]

The figure 2.7 shows the opened and closed cages. The size reduction and practicality gain is apparent in the folded configuration (B). The inspiration for the cage was origami structures, since they have shown high strength-to-weight ratios, high size reduction when folded, and are simple. A multicopter with a cage was built in order to validate the created design. The objective was to carry 500 grams of weight. The cage is made of several repeated foldable segments connected to each other, meaning if necessary more could be added or removed. The tubes are made of carbon fiber and the foldable joints are made of a 3D printed flexible material, which permits the folding action. The material choice is critical because rigidity is highly important, in order to prevent as much as possible undesired oscillations of the cage and cargo during flight. The model is somewhat scalable since it was calculated that while the mass may increase 3 times, the radius of the cage will increase less than 2 times, for example. The cage takes about 11 seconds to fold and about the same time to unfold. The cage has some expected negative effects on the flight capabilities: The total thrust generated by the propellers goes down from 1.2 kg without the cage to 1.06 kg with the cage, and the average drag coefficient goes from 0.723 without the cage to 1.226 with the cage.

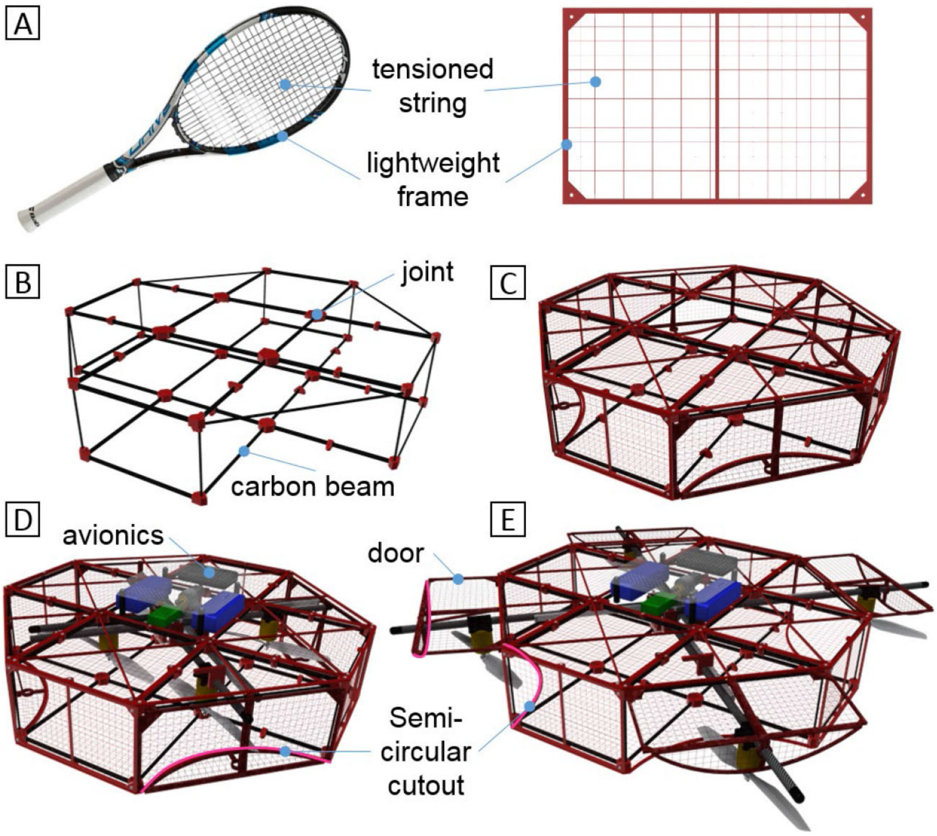


Figure 2.8: Another implementation of a "caged" drone, showing the inspiration for the cage wiring, the frame, and the complete drone in the retracted and extended configurations.[7]

Figure 2.8 shows a different type of cage implementation in a cargo quadcopter. This cage was explored in [7] and the focus was ensuring overall safety for humans (especially in last-mile delivery), even for small children. While other cages have large enough openings for fingers to fit in, this cage has holes small enough that even a 3-year-old children's fingers won't fit inside. This makes the drone easy to catch and hold, facilitating deliveries. In order to avoid excess weight and drag from a conventional high-density cage, and the increased danger to humans of a low-density cage, the drone can morph into one of two configurations mid-flight. The first configuration, as seen on "D", is a fully protected drone with retracted propellers. The second configuration, as seen on "E" has the propellers out of the cage and fully extended. The parcel is on top of the drone to avoid blocking the downward airflow from the propellers. The drone has a proprietary system for managing its configuration, with a DC motor extending and contracting the drone's arms, which also opens and closes the cage doors, which can be seen in figure 2.8. This way, the best of both options can be obtained: a high-density cage for safety, with the efficiency and drag of a low-density cage.

The first configuration, with retracted propellers fully inside the cage, was mainly designed to prevent any danger to humans or animals and consequently is used in takeoffs and landings. The second configuration is mainly for cruise flights at high enough altitudes, where there is no danger to humans from the exposed propellers. The extended arms provide a more efficient and stable flight. The lift is increased by 0.6 kg in this configuration, even though the system for arm deployment weighs only 0.17 kg.

The prototype cage itself weighs 0.38 kg, 15% of the total weight. It is made of carbon fiber tubes, plastic connectors, and very strong and thin string, with a weave inspired by tennis rackets with tensioned string.

Both of the aforementioned drones are capable of carrying 0.5 kg; however, the first is a lighter quadrotor at 0.8 kg and has a less dense cage that weighs only 0.15 kg, while the second is heavier at 1.5 kg for the quadrotor and 0.5kg for the cage and activation mechanism. It is clear a heavier cage will need more thrust and, consequently, a heavier quadrotor to supply that extra thrust.

2.2.4 Value-sensitive design of drones

Ethical considerations must be taken into account when designing drones for mass implementation. The authors of [8] created and implemented an ethical framework based on "Value-sensitive design" to develop technology for the "good of society".

The reason for implementing this framework is the case of "HealthDrone", a blood sample transportation drone. The objectives are to improve healthcare outcomes, reduce costs and improve sustainability. The study is focused on two Danish hospitals spread over 46 kilometres. At the time, the

Figure 2.9: The HealthDrone is based in a widely available hybrid drone, the wingcopter 178.[8]

The drone pictured in 2.9 is the generic frame for the HealthDrone. It is white and has wings and several propellers, making it a hybrid. It weighs 8.4 kilograms without any cargo or batteries, belonging to the heaviest weight category allowed in Denmark.

The technical objectives for the drone design are the ability to carry at least one blood sample and to be as light as possible because of safety and legal reasons.

The created ethical framework based in [26] consists of five principles:

2.2.4.1 Beneficence

Technology should benefit humanity—the project intends to benefit human physical health, welfare and environmental sustainability. This could be achieved by reducing waiting time for sample analysis, which means quicker treatment for the patient and less effect on public health. Currently, samples are transported by car once or twice a day, taking 30-45 minutes. The drone could do it in around 30 minutes and more frequently than the car. The benefits for humanity would reside in the reduced expense of operating an electric drone instead of a car, benefitting Danish taxpayers. Using electric motors, which the creators expect, would make it more sustainable than a car using fossil fuels.

2.2.4.2 Non-Malefiecence

Technology should not harm humanity. Security, privacy, jobs and the environment should all be considered when designing new tech.

One key goal of the project is that the drone be comparatively safe for commercial aviation, which means less than one fatality every ten million flight hours. If this is the case, the drone would be slightly safer than the current method of transportation. Choosing a path that avoids any possibility of human contact is the indicated solution to this concern.

A safety risk connected to this drone is the potential to carry infectious blood, which should be contained in safe containers to minimize danger.

Privacy violations were one of the key concerns: the drone would not have an installed camera, but the general population might not know this at first, so the perception of privacy would still be violated.

The drone could impact the jobs of the currently employed couriers, however, not in significant numbers (at least in the studied case.)

Other less probable/impactful risks and concerns were considered, such as environmental impacts from increased use and potential collisions with flying animals, among others.

2.2.4.3 Human Autonomy

"This principle relates to freedom and is associated with the values of human agency and responsibility". Agency includes human control over autonomous systems. Autonomy will not be subtracted because there is no correlation between patients and the transportation process.

2.2.4.4 Justice

The principle of justice is the fair distribution of benefits and harms to all involved. Because of the benefits referred, such as cost savings and faster treatment, all would benefit t in some way. Any drawbacks, such as the referred risks, would be applied mostly to those living near both hospitals and drone paths. Automatizing healthcare logistics could contribute to the unemployment of current workers, but government-sponsored training could mitigate this.

2.2.4.5 Explicability

The principle of explicability connects to how easily someone can understand the concept behind the implementation. It was observed that when a drone was more than 50 meters away, people reported feeling "comfortable". The authors aim at an altitude of 100 meters for normal cruising without unpredictable movements. However, it was noted that this distance could be counterproductive as it would be hard to see the drone and comprehend what it is. Experiments concluded that people expect a nearby human operator when they see a drone and will look around for the pilot. However, the drone is expected to eventually operate automatically with supervision, reducing accountability.

2.2.4.6 Redesign

Figure 2.10: FrugalDrone: Redesigned HealthDrone.[8]

The redesigned drone should support the principles mentioned above. The proposed drone is shown in Figure 2.10 and was renamed "FrugalDrone". Its wings span 1 meter, range 60 kilometres, can carry 250 grams, and weighs 1 kilogram. The drone is catapulted for takeoff and captured in a net for landing, which reduces the weight of the previous hybrid drone.

It is expected to take 1 hour for the trip between the two hospitals, moving at 43 kilometres/hour, and it will be launched as soon as a sample needs analyzing, which means less waiting time and faster treatment for patients.

Its low speed and weight aim to reduce injury in case of accidents with a person. Its battery is small in case of ingestion by an aeroplane engine. It is as light as can be relating to Danish laws and in the lowest level of risk.

2.2.5 UAVs for disaster management

Disasters pose a significant threat to human lives; search and rescue operations within the first seventy-two hours are the most important for maximizing survival chances. However, the lack of communication and situational awareness during disasters reduces the efficacy of first responder teams, with them resorting to improvisation and suffering reduced mission efficiency.

In [9], the authors explore the latest advancements in UAVs used for network-assisted first response to disaster management. UAVs provide incredible situational awareness during disasters, which otherwise is very hard to obtain. First responders gain a new perspective on emergencies, enabling them to assess damage, identify affected structures, evaluate transportation infrastructure, and estimate the number of people impacted. Considering this knowledge, first responders can comprehensively understand the disaster's impact, enabling effective response strategies. While some countries might have restrictions on UAVs, special authorizations are typically granted during such events to facilitate emergency responses.

Some of the potential uses for UAVs in emergencies are:

2.2.5.1 Reconnaissance and Mapping

UAVs operating in networked formations can perform reconnaissance and mapping, providing real-time data on the affected area. This information is critical for aid workers, helping them understand the extent of damage and identifying the critical areas requiring attention.

2.2.5.2 Structural Assessment

UAVs with cameras can help assess the structural state of buildings and infrastructure, helping first responders determine whether areas are safe for rescuers.

2.2.5.3 Search and Rescue Operations

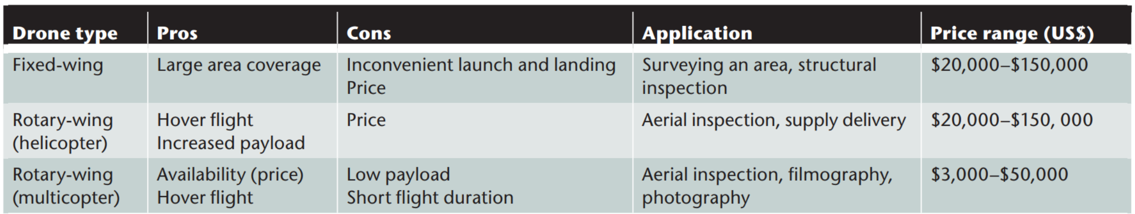
UAVs can identify stranded survivors from their elevated vantage points, accelerating the search and rescue process.

2.2.5.4 Ad Hoc Communications Infrastructure

UAV networks can serve as ad hoc communications infrastructures, allowing first responders to maintain contact and coordinate more effectively and allowing affected people to communicate valuable information.

2.2.5.5 Example application

In an example scenario proposed by the authors, main stations equipped with fixed-wing and rotary-wing UAVs would be deployed. Because of their fast flight capabilities, fixed-wing UAVs would perform rapid disaster area surveys and identify critical locations. Because of their hover flight capabilities, Quadcopters are dispatched to hover above these locations to gather real-time information. The main stations would be capable of storing multiple UAVs and equipped with communication antennas and power generators, ensuring continuous operation and UAV battery recharging.



Drone type	Pros	Cons	Application	Price range (US$)
Fixed-wing	Large area coverage	Inconvenient launch and landing Price	Surveying an area, structural inspection	$20,000–$150,000
Rotary-wing (helicopter)	Hover flight Increased payload	Price	Aerial inspection, supply delivery	$20,000–$150, 000
Rotary-wing (multicopter)	Availability (price) Hover flight	Low payload Short flight duration	Aerial inspection, filmography, photography	$3,000–$50,000

Figure 2.11: Division of UAVs by type and respective characteristics [9].

The figure 2.11 shows the different types of UAVs considered for this example application. It can be noticed that only fixed-wing and multicopter types are used. Fixed-wing UAVs have a higher cost than multirotor UAVs and also inherently require some runaway or device for launching and landing. However, they are relevant because of their scouting abilities. Multirotor UAVs, especially if they have worse components when compared to the fixed-wing UAVs, will have less power and shorter flight duration, meaning one individual multirotor UAV might not be as useful as one individual fixed-wing UAV; However, their advantages come from their hover abilities and large amounts of them deployed at the same time, which allows having multiple cameras and sensors working at the same time, supplying the necessary data for emergency operations, and permitting setting up ad hoc communications infrastructures.

2.2.6 Autonomous Indoors flight

It is common knowledge that GPS does not work indoors, as buildings are usually made of materials that block line-of-sight from the GPS module to the satellites required to pinpoint position, which means that any UAV operating indoors will depend on alternatives for determining position, attitude and velocity. UAVs could have interesting applications in indoor environments if they could accurately and reliably know their attitude and position; overcoming this challenge is no simple task; however, the possibilities that come from this would be near limitless.

Figure 2.12: Left: images from an indoor office environment. Right: images from an outdoor environment. [10].

Indoor environments differ significantly from outdoor ones, as can be seen in 2.12 posing several difficulties but also some advantages. They are shielded from wind and weather conditions like rain and fog, permitting extremely stable flying. However, indoor spaces have limited flying space, which makes flying more complicated and unreliable than in near-unlimited flying spaces outside. It is also common for there to be several obstacles indoors, further complicating object avoidance. Objects in indoor environments have diverse colours and textures, and some areas may lack significant texture (for example, white walls), which can complicate computer vision that relies on texture for matching; Furthermore, some rooms might have windows or mirrors, further complicating this already complicated problem.

The authors of [10] predict that a UAV adapted to indoor flight would be small and able to fly slowly, as this reduces both the probability of collisions and permits a slower response time for making directional adjustments. Fixed-wing aircraft are ruled out for indoor flight as they require large wings, high speeds and wide spaces. Multirotors are pointed as a good solution, as they have hovering abilities. However, they actively depend on IMUs and autopilot because of their inherited instability; This means that long-term bias will accumulate from uncorrected attitude estimates, resulting in a drift of the multirotor UAV to a specific direction. It can be deduced that this drift will eventually lead to a collision with an obstacle. The biases must be corrected using velocity or position measurements.

GPS has been ruled out above, as it does not function indoors. Other alternative sensors must be used. A common and simple solution for avoiding drift is using an optical flow sensor pointing downwards, which uses various sensors to detect changes in ground texture and visible features. These changes can be used to detect the drift direction and compensate for it. However, many types and combinations of sensors can be applied to solve this problem and augment a drone's indoor capabilities [27, 28, 29]

2.2.7 VTOL UAVs

The idea of a multirotor UAV can be attractive for its ease of taking off and landing, as well as its hovering capabilities. These benefits can be applied to bigger standalone systems, giving them these desirable capabilities. The clearest example of this is Fixed-wing vertical take-off and landing (VTOL) UAVs, which combine two types of UAVs in one, fixed-wing and multirotor.

Figure 2.13: 3D rendered model of a VTOL UAV designed in [11].

As can be seen in 2.13 VTOL UAV consists of a body similar to a fixed-wing UAV, with a fuselage, wing, tail and horizontal motor combined with the upward-pointing motors of a multirotor UAV. It is very common for there to be four upward-pointing motors.

VTOLs are most relevant in missions that benefit from a fixed-wing and multirotor being used together. The vertical take-off and landing associated with the multirotor part eliminates any need for a runaway or catapult, broadening the craft's mission availability. The hovering abilities can be beneficial in many situations, such as aerial observation and data collecting, or simply keeping the vehicle airborne without movement. The increased power efficiency of using the very efficient fixed wing during the main part of the mission can significantly increase air time. The result is much more flexible than its fixed-wing or multirotor UAV counterpart because it combines both. VTOL UAVs of this type have been researched and tested widely [11, 30, 31, 32]

2.2.8 Battery dumping

Nearly all electric motor UAVs are operated by drawing energy from a battery carried in their body. The battery weight is usually a significant part of the total UAV weight, and it is nearly always assumed the weight is constant throughout the flight, which makes sense considering batteries do not lose weight as they use up their charge. However, it is possible to split a battery into parts and discharge each part individually, dumping it when completely discharged and progressively reducing the aircraft's weight. The authors of [12] studied expanding flight time/range by dumping exhausted batteries during flight.

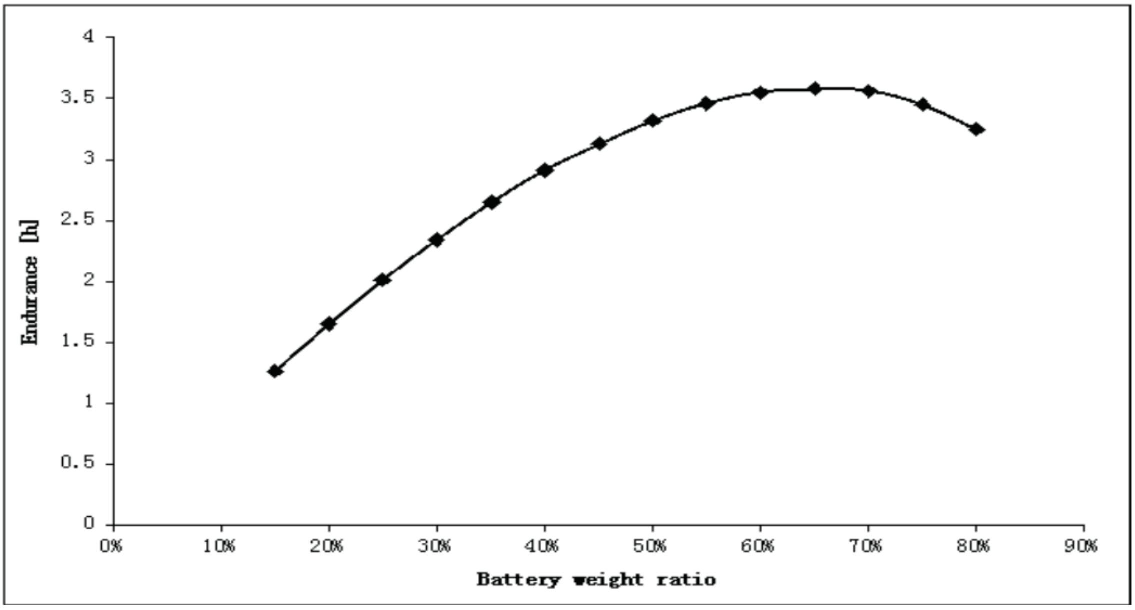


Figure 2.14: Curve of battery endurance in relation to weight ratio. [12]

Figure 2.14 demonstrates that heavier, higher-capacity batteries do not necessarily mean increased longer endurance. Initially, a bigger battery equals more endurance; However, it is worth noting that there are diminishing returns here. Eventually, a turning point occurs where even bigger batteries result in less endurance, at around 65% of the battery's total weight ratio. The explanation behind this phenomenon is that the motors must make more power to carry higher weights and that the motor's efficiency is not constant; The more power consumed, the less efficient the motors are.

The authors took inspiration from combustion engines: their fuel is entirely used up and leaves no "deadweight" within the fuselage. The aircraft could benefit from increased range if something similar could be applied to batteries.

The proposed system is one where the battery is divided into smaller battery packs that can be used individually and dumped after being exhausted. The system will bring additional weight and, consequently, higher power consumption, which must be considered.

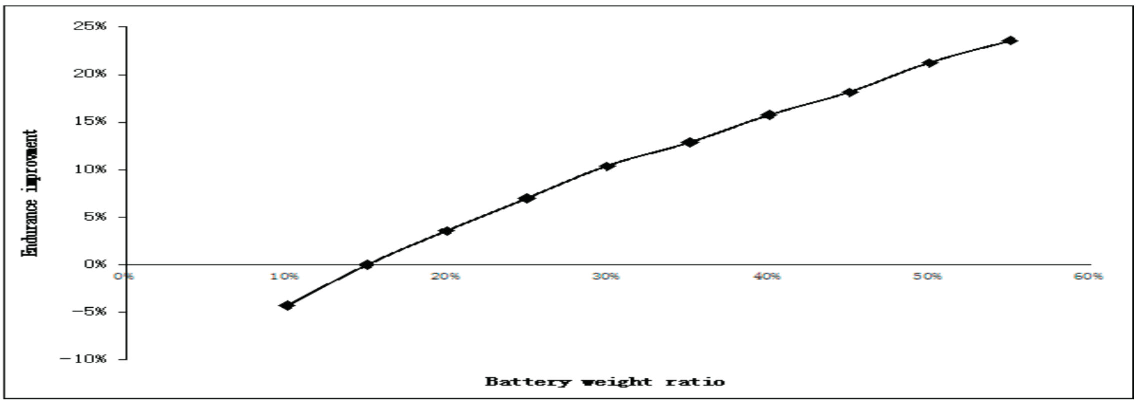


Figure 2.15: Curve of battery endurance improvement in relation to weight ratio, with the implemented pack system, using two packs. [12]

Figure 2.15 shows the resulting calculations using the novel system, with the battery split into two packs. The system is not beneficial for UAVs with lightweight batteries compared to the total craft weight; However, improvement is observed with higher battery weight ratios, which is appropriate since one can assume that UAVs with bigger batteries are trying to maximize endurance. The results are promising as it points towards the benefits greatly overcoming the excess weight from the system.

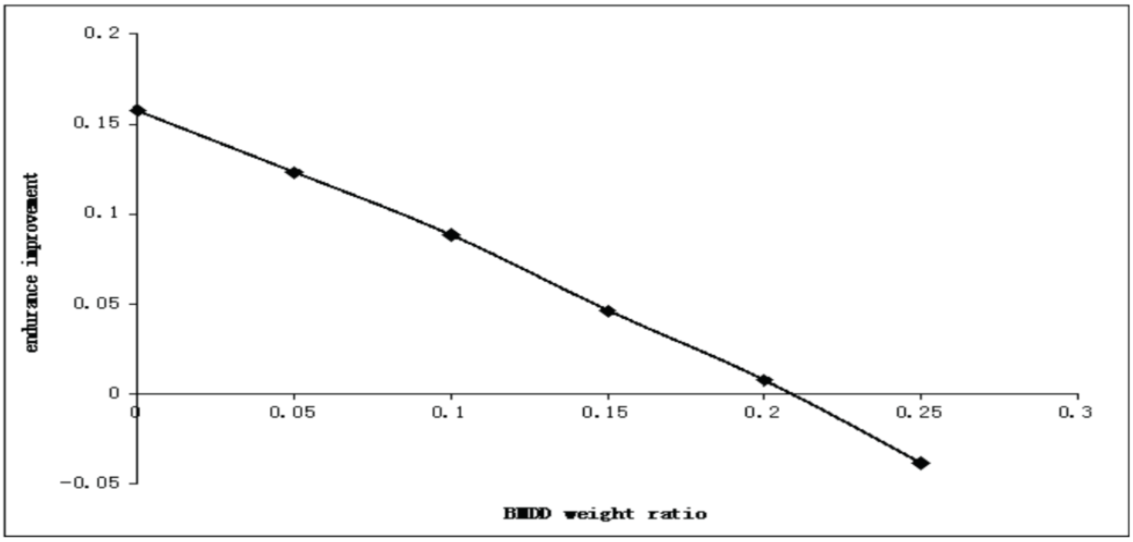


Figure 2.16: Endurance improvement in relation to the excess weight of the battery mounting and dumping device. [12] This graph was calculated for a system with two packs and a 0.4 battery weight ratio.

The figure 2.16 shows that the mounting and dumping device system has to be somewhat lightweight, or else all gained endurance will be lost because of the excess weight of the system, which makes sense since the overall purpose of the system is to reduce the load on the craft and consequently reduce spent power, which will not happen if the system itself weighs a significant amount.

This theoretical system shows promising numbers which may benefit UAVs operating in controlled ambients where batteries could be easily recovered, for example, inside a factory.

2.2.9 Identification and elimination of pests

Taiwan has a problem with pests feeding on litchi and longan fruits. The damage done affects the yield and quality of these fruits enough that the authors of [13] explored a solution to this problem. For this, they implemented two different drones: The first drone is a reconnaissance drone responsible for detecting the pests by photographing them and marking their location. The second drone is an agricultural drone responsible for carrying and spraying the pesticide directly on the pest.

The study uses artificial intelligence, specifically the deep learning model Tiny-YOLOv3 running on an NVIDIA Jetson Tx2, an AI computing device. This board is installed in the reconnaissance drone so that it can identify its target in real time. After identifying the targets, the board also plans a path for the agricultural drone to follow and spray pesticide directly on the pests, which uses the DQN path algorithm.

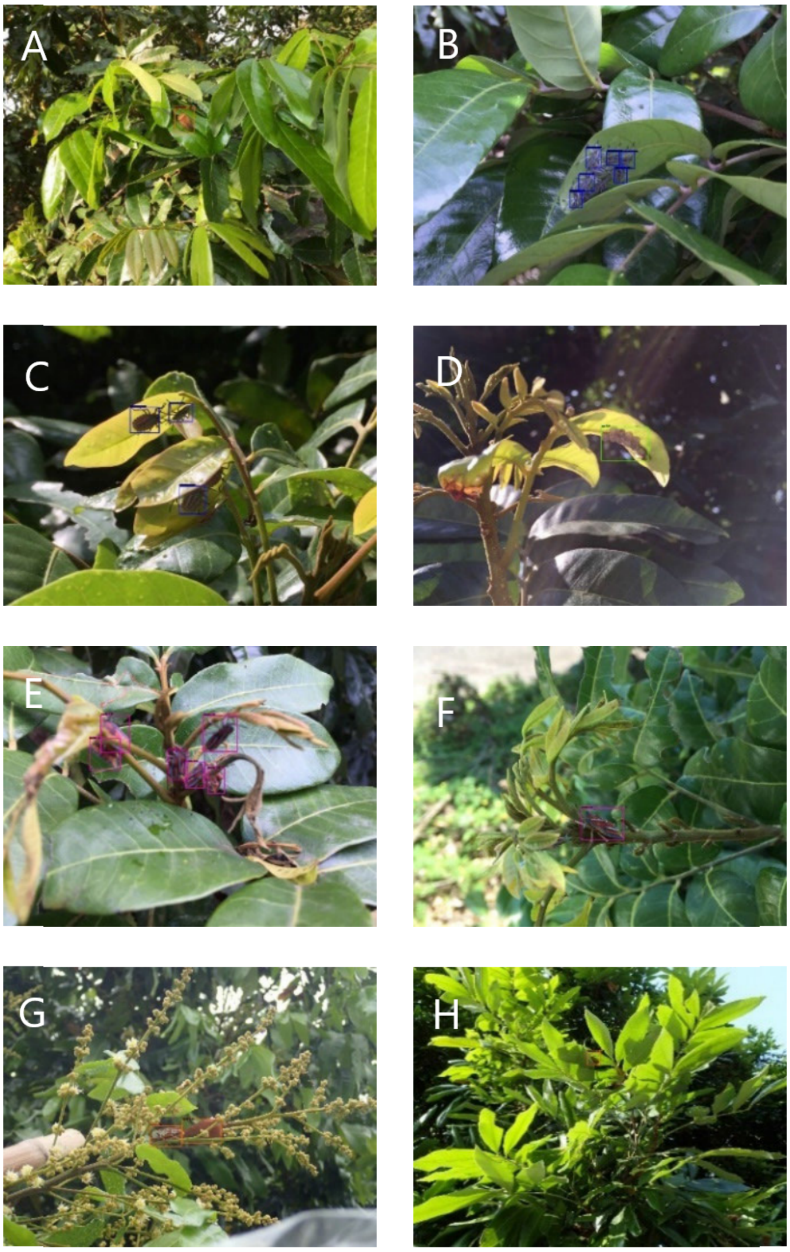


Figure 2.17: Pests as identified by the Tiny-YOLOv3 model. [13]

The model could effectively identify the pests, as shown in figure 2.17. It was determined that it reduced water consumption by 87.5% compared to the traditional method of spraying pesticides and reduced the agricultural drones' operating time by 53% compared to the manual method of spraying.

2.2.10 Management of Motor Failures in a Hexacopter

Hexacopters with normal control schemes may crash if one or more motors fail during flight because there is no system to detect and compensate for failed motors. In "Analysis and Management of Motor Failures of Hexacopter in Hover" [14], the authors studied and developed an allocation algorithm for cases where motors fail during hovering. This algorithm can supply limited control in failures of up to three motors concurrently.

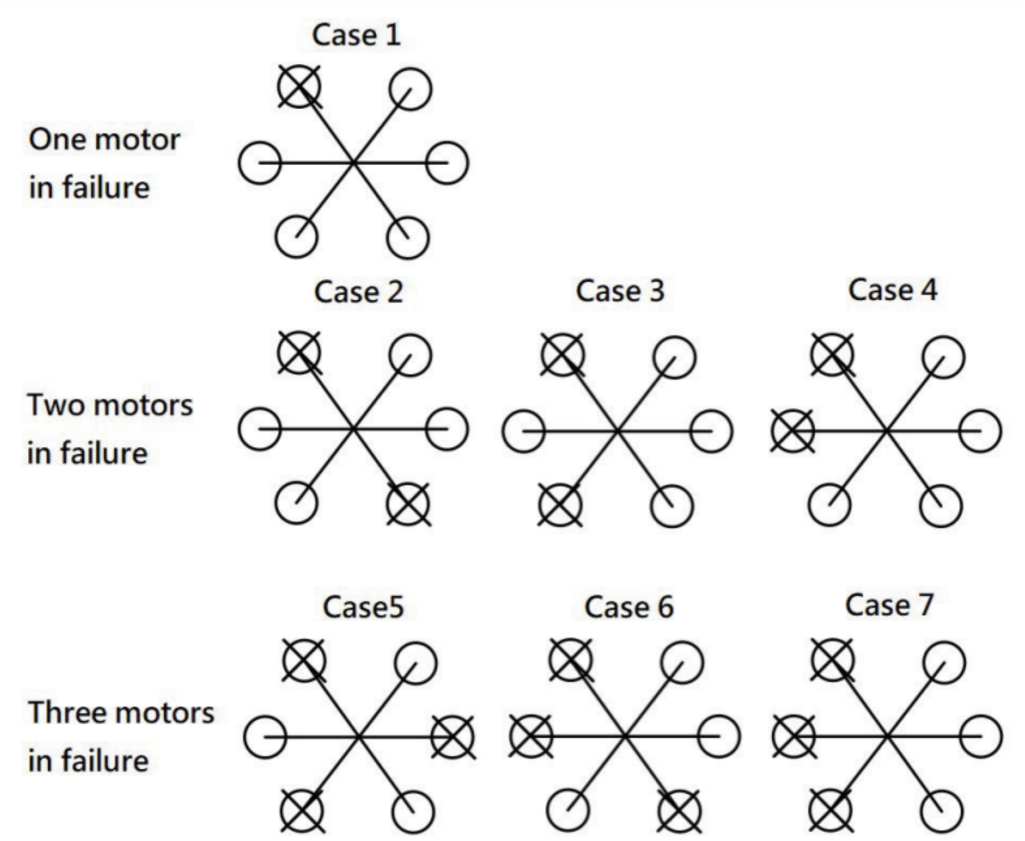


Figure 2.18: The various cases and configurations of failed motors studied. [14]

With the data of failed motors collected, an allocation matrix is developed to distribute the control forces among the working motors. The studied cases can be seen in 2.18. In the case of two opposite motors failing (case two), the operator can regain some control over the drone, performing roll and pitch operations. It was found that in the case of one motor failing (case one), the best option is to turn the opposite motor off, which equates to the case referred to above. With two failed motors with one working motor in between (case three), some control can be regained, but the hexacopter tends to spin and wobble. In case five, where three motors fail with a motor in-between each, it is possible to regain some control other than yawing, but it was considered very unstabled as it tends to spin and wobble. In the remaining cases, it was difficult for a pilot to regain control and finish a safe landing.

Chapter 3

Prototype Design

The choice of configuration and parts for the actual drone will be discussed in this chapter. Drones have different necessary and non-necessary parts, which will be addressed in this chapter.

The main objective was to project and build a prototype drone capable of lifting at least 1 kg, with a flight time of at least 5 minutes when the craft is carrying this weight. Security was also of the utmost importance since the intention was for the craft to run indoors.

It was decided that a hexacopter frame would be an adequate solution for this purpose. Even though a quadcopter capable of lifting more than 1 kg is easily achievable, it made sense to prototype a hexacopter because, as stated before, it offers redundancy, which in the theme of carrying cargo is very important. This permits emergency flying and landing, while a quadrotor would lose control, act unpredictably and maybe crash.

3.1 Frame

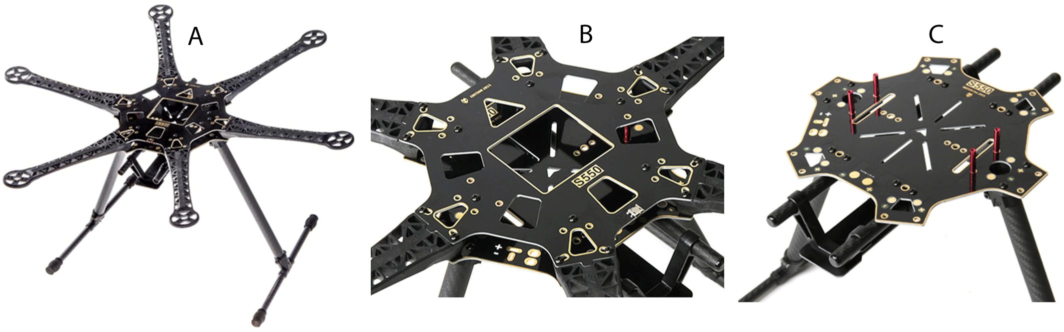


Figure 3.1: The obtained frame. [1]

Our frame choice can be seen in figure 3.1. It can have propellers up to 10 inches or 254 millimetres in diameter. It has built-in power distribution which will not be used because the amount of current estimated to be drawn from the batteries would surpass its maximum permitted current. The distribution is done through the centre plates. All plates are made of fibre-reinforced plastic. The drone has two plates in its centre, as shown in figure 3.1 (B). Under the lower plate, connected to 2 carbon fiber rods, are two small plates: one is for attaching a camera or a gimbal. The arms are made of plastic reinforced with a metal rod. The plastic was moulded into a type of net.

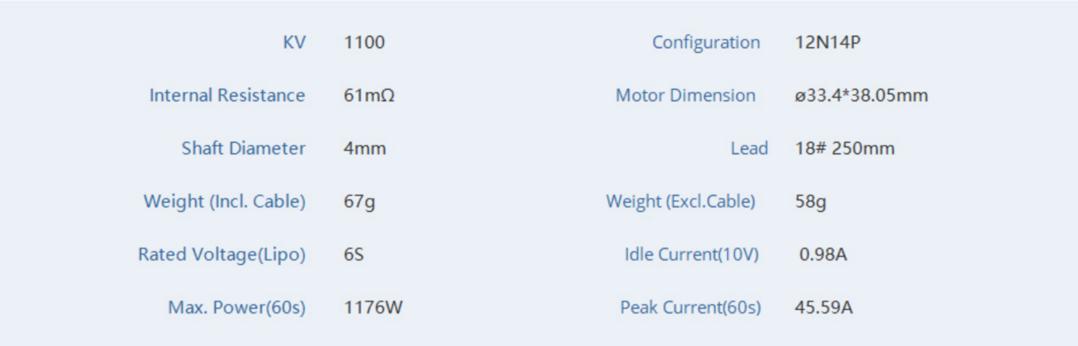
The landing gear is included with the frame and provides a stable surface for the drone to land on. It is made of two carbon fibre tubes and plastic connectors, making it very light.

Velcro straps were obtained for temporarily fastening the batteries to the drone body. These will attach to both plates in the underbelly of the drone.

3.2 Motors

It was important to choose a reliable and dependable motor. Because of this, a known brand was chosen, and a motor was selected from their options. The motor's identifier is F100. The manufacturer's suggested use for the selected motor is carrying video cameras for filming purposes, which requires both power and stability.

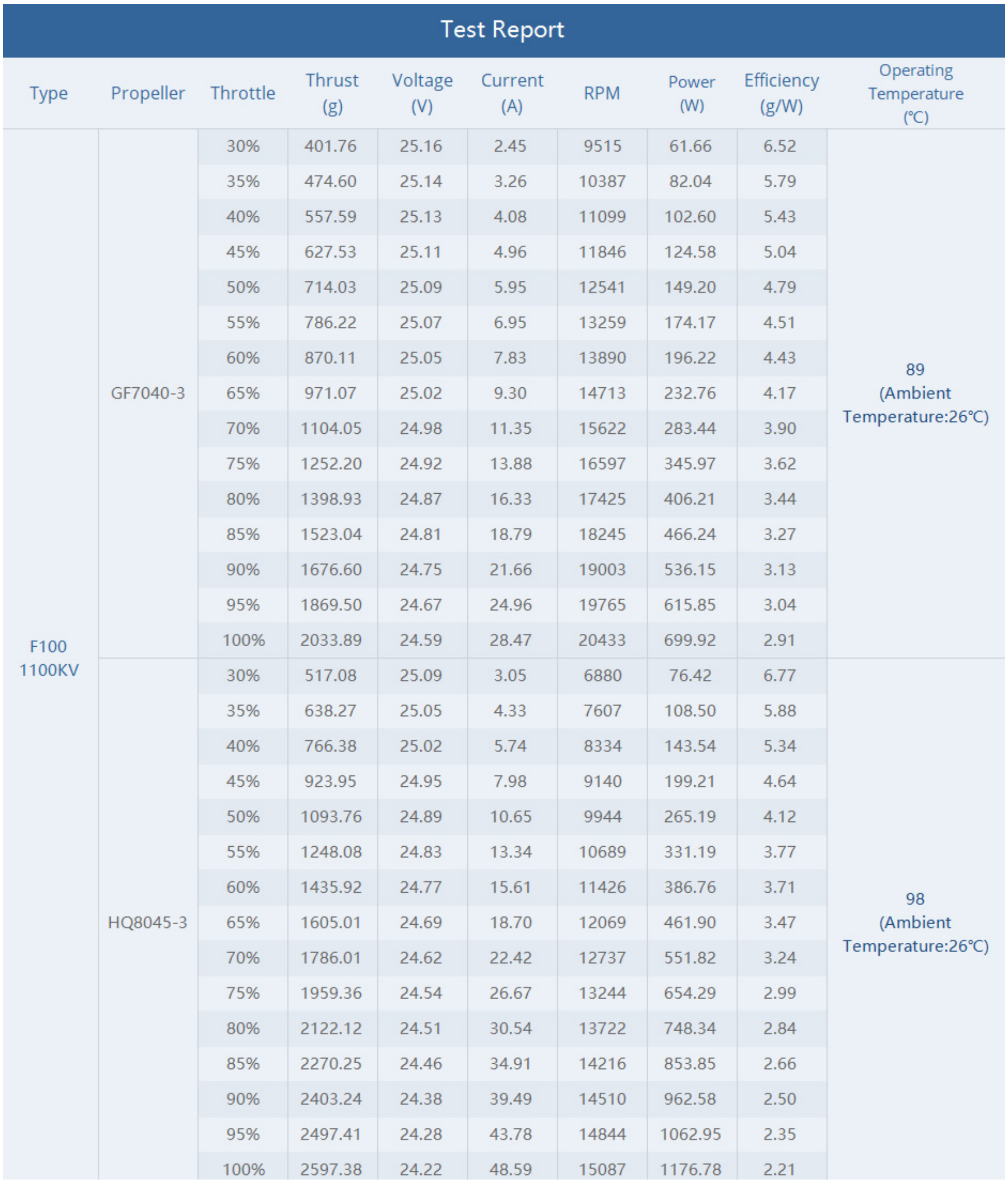
The chosen motor has two Kv rating options: 1100 Kv or 1350 Kv. Kv is the constant of motor velocity. It measures the number of revolutions per minute a motor accomplishes per volt supplied when no load is attached to the motor shaft. It is a general rule that for the same motor, a lower Kv rating will result in a lower maximum thrust but higher efficiency for the same value of thrust. Because of this, it was decided that getting a bigger motor with lower Kv was a good choice, as battery life is so important and, consequently, so is efficiency.



KV	1100	Configuration	12N14P
Internal Resistance	61mΩ	Motor Dimension	ø33.4*38.05mm
Shaft Diameter	4mm	Lead	18# 250mm
Weight (Incl. Cable)	67g	Weight (Excl.Cable)	58g
Rated Voltage(Lipo)	6S	Idle Current(10V)	0.98A
Max. Power(60s)	1176W	Peak Current(60s)	45.59A

Figure 3.2: Motors specifications for the F100 1100Kv, obtained from the manufacturer. [15]

The motor specifications can be seen in figure 3.2. Some important information can be deduced here, such as the maximum sustained current, which is 45.59 Amperes and the total weight including the cables, which is 67 grams.



Test Report

Type	Propeller	Throttle	Thrust (g)	Voltage (V)	Current (A)	RPM	Power (W)	Efficiency (g/W)	Operating Temperature (℃)
F100 1100KV	GF7040-3	30%	401.76	25.16	2.45	9515	61.66	6.52	89 (Ambient Temperature:26℃)
		35%	474.60	25.14	3.26	10387	82.04	5.79	
		40%	557.59	25.13	4.08	11099	102.60	5.43	
		45%	627.53	25.11	4.96	11846	124.58	5.04	
		50%	714.03	25.09	5.95	12541	149.20	4.79	
		55%	786.22	25.07	6.95	13259	174.17	4.51	
		60%	870.11	25.05	7.83	13890	196.22	4.43	
		65%	971.07	25.02	9.30	14713	232.76	4.17	
		70%	1104.05	24.98	11.35	15622	283.44	3.90	
		75%	1252.20	24.92	13.88	16597	345.97	3.62	
		80%	1398.93	24.87	16.33	17425	406.21	3.44	
		85%	1523.04	24.81	18.79	18245	466.24	3.27	
		90%	1676.60	24.75	21.66	19003	536.15	3.13	
		95%	1869.50	24.67	24.96	19765	615.85	3.04	
		100%	2033.89	24.59	28.47	20433	699.92	2.91	
	HQ8045-3	30%	517.08	25.09	3.05	6880	76.42	6.77	98 (Ambient Temperature:26℃)
		35%	638.27	25.05	4.33	7607	108.50	5.88	
		40%	766.38	25.02	5.74	8334	143.54	5.34	
		45%	923.95	24.95	7.98	9140	199.21	4.64	
		50%	1093.76	24.89	10.65	9944	265.19	4.12	
		55%	1248.08	24.83	13.34	10689	331.19	3.77	
		60%	1435.92	24.77	15.61	11426	386.76	3.71	
		65%	1605.01	24.69	18.70	12069	461.90	3.47	
		70%	1786.01	24.62	22.42	12737	551.82	3.24	
		75%	1959.36	24.54	26.67	13244	654.29	2.99	
		80%	2122.12	24.51	30.54	13722	748.34	2.84	
		85%	2270.25	24.46	34.91	14216	853.85	2.66	
		90%	2403.24	24.38	39.49	14510	962.58	2.50	
		95%	2497.41	24.28	43.78	14844	1062.95	2.35	
		100%	2597.38	24.22	48.59	15087	1176.78	2.21	

Figure 3.3: Motors tests run by the manufacturer. [15]

The factory motor test can be seen in figure 3.3. These tests use two different propellers, a 7-inch and an 8-inch. Measures are taken at several throttle points, measuring the generated thrust, the battery voltage, the supplied current, the RPM, consumed power, and the efficiency, which is measured as grams of thrust per consumed power in watts. One key takeaway is how the bigger propeller is more powerful and efficient than the smaller one.

Using the data from the "HQ8045-3" propeller, an eight-inch, three-bladed propeller, we can see that the absolute maximum thrust per motor is about 2600g. Generally, it is common to admit that the maximum weight of the craft in real flying conditions should be at maximum half of this value; following this general rule, the total thrust from the 6 motors would theoretically be able to lift 7800g.

It is worth noting that there is market availability of motors capable of fitting in a quadcopter frame and lifting this amount of weight, but for the reasons referred to at the beginning of this chapter, a hexacopter configuration was chosen.

3.3 Propellers

The propellers are directly linked to the motors, both physically and theoretically, as different size propellers are adequate for different motors. The chosen motor is designed for 7 or 8-inch 3-bladed propellers, which is indicated by the propellers used for motor testing by the manufacturer.

Two different types of propellers were bought: One type being "GEMFAN 7040-3", with three blades, 7 inches of radius, and 4 inches of pitch, made of polycarbonate; and a second type, "GEMFAN 8040-3", with three blades, 8 inches of radius, and 4 inches of pitch; made of reinforced polycarbonate. The main differences are the radius of the blades and the material.

A 3-blade propeller was chosen as it was considered a good equilibrium between performance and efficiency. Compared to the common 2-blade propeller, they deliver more thrust but are less efficient; however, they can help maintain the drone smaller in size with high thrust.

A prop tool was obtained as it facilitates attaching and detaching propellers from the motors. This tool can easily be carried in a pocket as opposed to a ratchet.

3.4 Propeller guards

Because the rapidly spinning propellers are very dangerous to people and can cause damage to themselves and the surrounding environment, it was important to add propeller guards to the frame. This way, any lateral contact can be avoided by these protections.

These parts were printed using an Ender 5 3D printer. The printed parts are for propellers up to 13 inches, so they are enough for the chosen propellers. The material that was used to print them is polylactic acid (PLA).

The 3D model of the propeller guard was obtained online [33].

Figure 3.4: One of the printed guards after being modified.

Because the model wasn't completely adapted to our motor and frame choice, a small part of the printed plastic had to be removed by hand for better fitment. Plastic was removed from the circular base where the motors mount, as can be seen in Figure 3.4. Some plastic also had to be removed from the screw holes, as it was the only way the screws could pass through.

3.5 Electronic speed controllers

The ESCs are relevant for controlling the supply of current to the motors, and the differentiation of products usually comes in the maximum capacity of continuous currents. The chosen product was based on availability and price. Six "ZMR Bidirectional BLHeli_S ESC" were obtained, with the selected version supporting up to 80 Amperes of continuous current, which is more than enough for the chosen motors. Each individual ESC weighs 75 grams. Because these ESCs have the "BLHeli_S" firmware, they are programmable. They are adequate for 6S battery input.

3.6 Batteries

The batteries are crucial to the drone build, and many factors must be considered:

The first factor is the number of battery cells. The chosen motors are rated for 6S batteries (6 cells), so we must choose a 6S battery.

The second factor is the battery capacity. The drone must be able to fly for a reasonable amount of time.

The third factor is the battery discharge rate. The battery must supply current equal to at least the maximum current consumed by the motors (at 100% thrust). All RC Batteries have a discharge rating associated with them, from where we can extrapolate the maximum current draw. This is done by multiplying the battery capacity by its discharge rate.

The fourth factor is the battery connector. The connector at the end of the battery cable must be capable of supporting the current a battery supplies, which is not always guaranteed in situations of high current draws.

The fifth factor is the battery size and weight. The battery has to realistically fit on the drone frame, or else it might be hit by the propellers or make the drone very cumbersome. Its weight is an important factor, as more battery weight means less carriable cargo weight.

All these factors culminate in our choice of batteries. First of all, we opted for having 2 batteries on the drone body, as it splits the current draw and consequently removes the concern about the battery connector overcurrent and gives us more options on where to place the batteries in the frame. After that, we decided on a trustworthy company with a good supply of batteries. On their website, we looked for batteries that fulfilled all of the listed criteria. We chose a "TATTU 9000mAh 22.2V 25C 6S1P Lipo Battery Pack with EC5", which, as the name indicates, has a 9000mAh capacity. Multiplying by two, we get 18000mAh of total capacity in the drone. Four batteries were obtained in total, as this way, if it is necessary to replace the batteries in the drone, they can be replaced by completely charged spare batteries.

Theoretically, if the drone is run at 70% thrust, which enables it to carry at least 1350 grams while hovering, it should have just a bit over 8 minutes of flight time available.

A battery charger capable of charging 6S batteries was obtained; because there weren't any cables with the EC5 connector, one was created from two cables, one red and one black, and an EC5 connector.

Two LiPo bags were bought for the batteries for safety reasons: If damaged, LiPo bags can combust and explode, so it is important that they are stored and charged in a prepared environment. Whenever the batteries weren't being used, they were stored in these bags for safety reasons.

A Battery and receiver checker was obtained to check battery voltages swiftly. This tool makes use of the battery balance lead connector to power itself and receive the individual cell voltages. The checker also has other features, such as checking PWM, PPM, and S.bus inputs.

Two LiPo battery low voltage buzzer alarms were obtained. These go in the battery balance lead while the batteries are airborne and play a loud alarm when the batteries get to a low voltage.

This way, it can be safely detected when the drone should prepare for landing. They also have a screen that shows the total and individual cell voltage.

3.7 Flight controller

There are many flight controllers to choose from in the consumer market; however, most of them are created with small FPV quadcopters in mind. Most of them are a 2 in 1 board or stack of boards, with 1 board being the flight controller and the other board the power distribution board and ESCs. Because we have independent ESCs, a flight controller with included ESCs was unnecessary. However, it was important for the flight controller to have at least 6 motor control outputs, and it was necessary for it to be dependable. The chosen controller was the "Cube Orange+", which is "Designed for hobby users, commercial system integrators and UAS manufacturers" [34]. This controller contains the fastest processor available in the drone market, with a 480 MHz clock speed. Its board provides several interfaces, which permits adding a lot of peripherals (such as telemetry modules, GPS, IR sensors, optical flow sensors, and cameras). It has one redundant processor, three redundant Inertial measurement units, and one redundant power supply, providing an extremely dependable system.

An SD Card was bought and inserted into the flight controller for logging telemetry.

3.8 GPS module

The chosen GPS module is the "Here3", which is compatible and suggested by the flight controller manufacturer. This module uses the CAN bus for communicating, meaning it is nearly plug-and-play with the chosen flight controller. It supports RTK GPS, allowing for very accurate positioning in ideal conditions. Its plastic cover creates trustable protection from the environment, and the included stand provides advantageous positioning in the drone frame. The GPS has LEDs that provide information on the current state of the flight controller.

3.9 Power distribution

Because the motors may draw very high currents, finding a safe and trustable system for power distribution was critical. It is common for the ESCs to be directly soldered to a circuit board that only has conductive tracks with a high current capacity; however, this solution has several downsides: Because the ESCs are soldered, they cannot be swiftly swapped; a circuit board does not provide an easy way to measure the current flowing through it, has no easy way of installing a kill-switch and has no compatible output port for providing main and backup power to the controller.

Given these facts, it was decided that a "smart" power distribution board was a good choice for the build. The "MAUCH 031 PDB" was chosen, with up to 400A continuous current capacity from 2 battery inputs, which is within the desired values; current sensors that output to the flight controller through the main power cable; fully redundant flight controller power supply, up to 8 outputs for ESCs with banana connectors and a built-in killswitch.

The 2 battery inputs have pairs of 10 AWG red and black cables, which have more than enough capacity for the battery output current. EC5 male connectors were obtained and soldered to each pair of cables, as the batteries are all EC5 female connectors. This way, the batteries can be easily connected and disconnected from the PDB.

3.10 Remote controller

The remote controller is responsible for sending instructions to the aircraft. It was important for this controller to be reliable, have desirable features, and have native ELRS support. The chosen remote was the "TX16S MARK II ELRS". The controller features hall effect joysticks, which are known for being more reliable than analogue joysticks. The controller has a handle for easy transportation.

Two 18650 batteries were obtained and placed inside the controller, in the appropriate place, for power. The controller features an inbuilt charger for the batteries.

3.11 Software

It is important to distinguish the two main software used in this work. The flight controller is a programmable computer with memory for installing software. Flight controller software controls every peripheral in the drone, such as the motors. Because a user has no way of directly interacting with the flight controller, such as a touchscreen, configurations can not be made directly. Therefore, there is specific computer software for programming flight controllers. This computer software permits connecting a computer to the flight controller using a USB cable. It enables configuring various settings, calibrating sensors, defining flight modes, adjusting control parameters, and performing firmware updates. This software is downloadable from the internet.

Ensuring the reliability of the flight controller software used in this context is extremely important due to the possible consequences of any bugs or failures. Such issues could lead to errors that result in the destruction of the drone or pose a risk to individuals' safety. An up-to-date, widely-used flight controller software with extensive documentation was considered very important.

The chosen solution was *ArduPilot*, and its associated Windows application, *Mission Planner*.

The software is updated often and is considered to be very stable. There is detailed and comprehensive documentation providing information and instructions on how to utilize each feature effectively.

User forums play a vital role in supporting this flight controller software. These forums serve as a platform where users can post questions, answers and engage in discussions related to the software. Anyone can read these discussions, and they help address common questions and provide valuable insights into using the software.

This application allows for extensive interaction with the flight controller by USB connection, allowing for easy calibration, configuration and tests.

Chapter 4

Product Assembly

4.1 Build Assembly

The motors, ESCs, and the power distribution board came without soldered connections, so all needed connectors to be soldered on. This process was done using a soldering iron, solder, and a tool for holding the cables and connectors while the soldering was being done. After the cables cooled down from soldering, the connector and cable were pulled apart from each other to check if the solder was completed correctly.

Figure 4.1: ESC cables after connectors were soldered.

In total, eighteen connectors were added to the motors' inputs, eighteen to ESCs' outputs that plug into the motors, twelve to the ESCs' inputs that connect to the power distribution board, and two to the power distribution board inputs where the batteries plug into. Figure 4.1 shows the output (left) and input (right) cables of an ESC after the soldering process was finished.

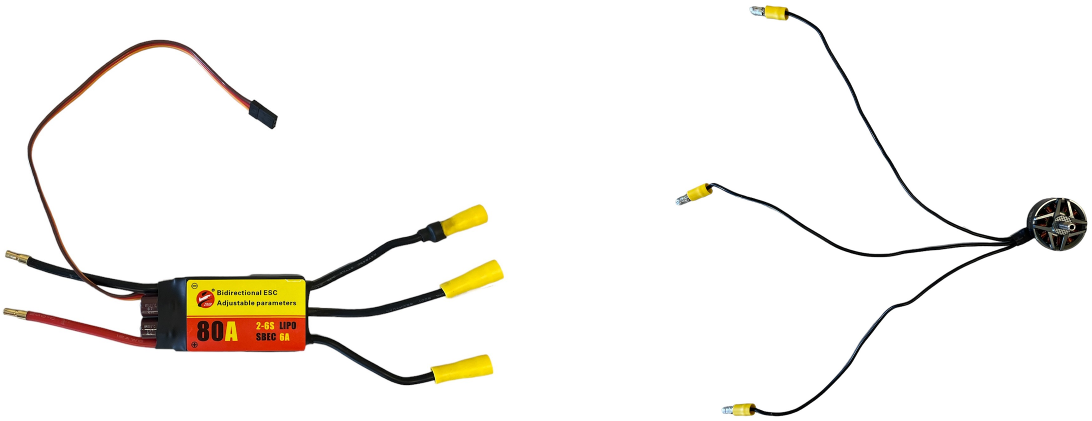


Figure 4.2: An ESC and a motor with the respective soldered connectors.

An ESC and motor after soldering was finished can be seen in 4.2. The type of connector between the motor and ESC is a "yellow bullet connector", which is intended to be crimped. However, the wires were soldered instead of crimped, as some were too thin to be crimped. The type of connector between an ESC and the power distribution board is the "banana connector", which was also soldered. Both of these connectors are visible in figure 4.1.

Figure 4.3: ESC and Motor connected together.

This process resulted in a modular wiring system, from the battery to the motor, as any piece can be removed without cutting or desoldering. This facilitates drone assembly and switching parts in case of failure. An ESC and motor connected together can be seen in 4.3.

Figure 4.4: One of the assembled frame legs.

The frame came in parts and needed assembly. The two legs were assembled first as they had crucial structural points for the rest of the build. One can be seen in figure 4.4. The carbon fibre tubes composing the legs can be seen in this picture. The cylindrical objects on both ends of the tube on the right are made of a sponge-like material and function as landing feet.

The propeller guards and motors were screwed onto the arms before being mounted to the frame, facilitating assembly.

Excessive vibration is very common in drones and can result in screws becoming loose. Threadlocker was added to half of the screws in each arm to guarantee that all do not fall out in extreme cases, but vibration-related screw-loosening can still be detected.

The arms and propeller guard mounting holes did not coincide with the mounting holes of the motors, and because they were plastic, it was decided that drilling them off with a rotary drill would be the solution. The rotary tool was also used to remove part of the propeller guard mounting point because excess plastic collided with the arm.

Figure 4.5: One of the arms with tidied cables.

With the arms and legs assembled, the frame could be put together. First, the arms and legs are mounted to a lower plate; then, an upper plate is screwed onto the top of the arms and support structures connected to the legs. The arms are supported above and below, proving to be a strong structure and reducing the probability of damage. Because the ESCs are attached to the motor wires, they needed to be tidied, and this was done using zip-ties, fixing all the wires and ESCs to the frame. An example of tied cables can be seen in 4.5. Tidying everything was important for cable management and avoiding the propellers hitting and cutting the cables midflight. If something needs to be replaced, zip-ties will have to be cut, but they are easy and fast to replace.

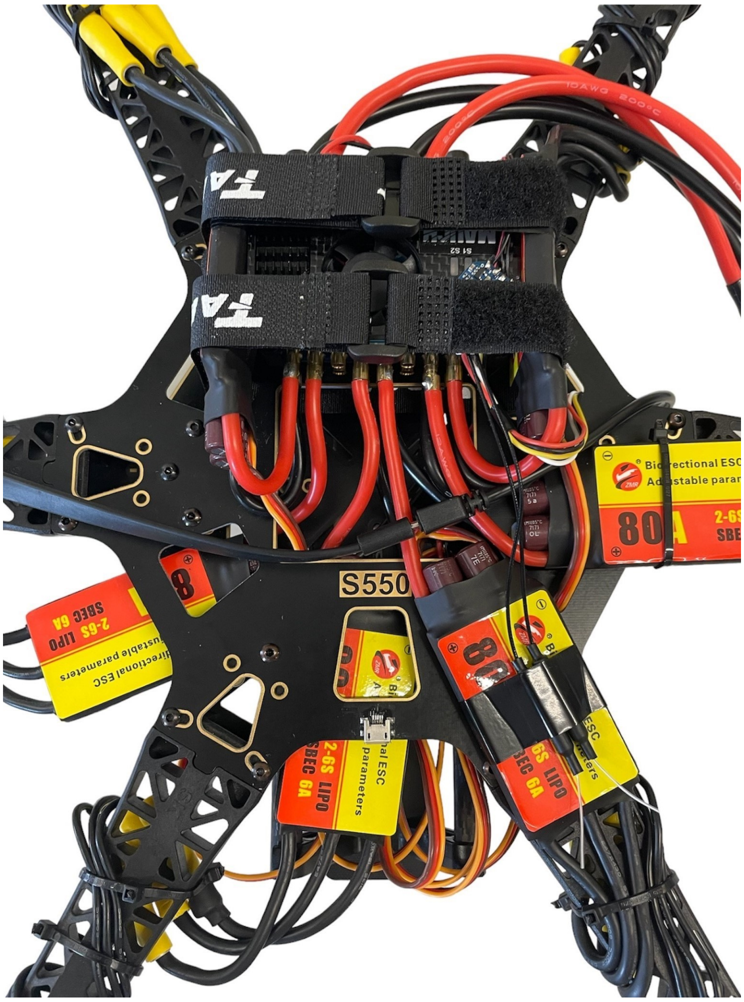


Figure 4.6: Power distribuition board with the connected ESCs.

The power distribution board was placed in the front part of the top plate and attached with two velcro straps that pass through the frame, fixing it in place. This place was chosen because the ESCs could be attached easily, independently from which arm they came. There was some difficulty with ESC connection and placement because their positive/negative wires were very short. Eventually, they were all connected and zip-tied in place, as shown in figure 4.6.

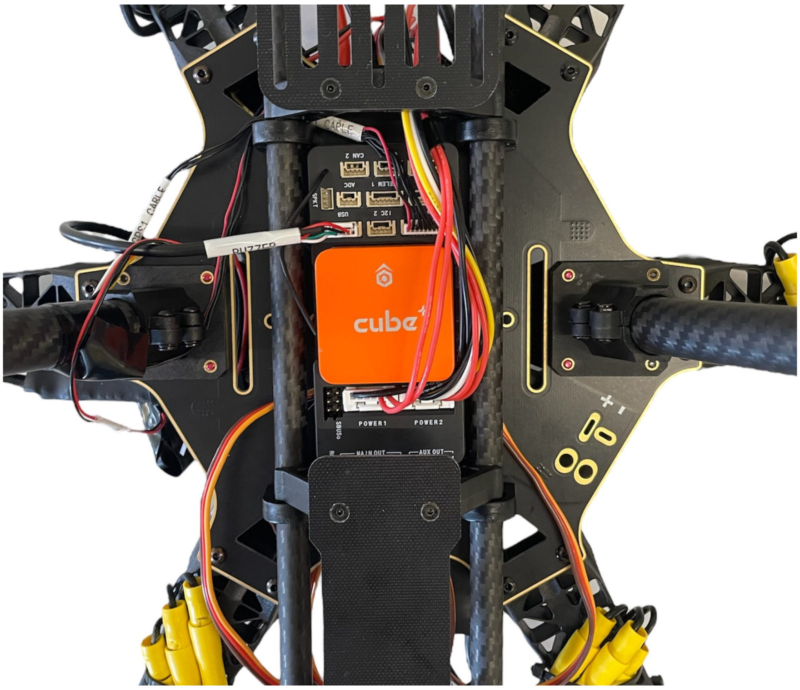


Figure 4.7: The flight controller attached to the bottom of the lower plate.

The flight controller was placed on the bottom of the lower plate, as shown in figure 4.7. This place was chosen because it was the only place where the flight controller could be aligned with the centre of the drone body, which is very important, and it is also a place where all cables were able to reach. It was glued in place with double-sided tape. It can be noticed that it was glued upside down; a special configuration had to be made in the flight controller register through Mission Planner for the controller to take this into account, but after the configuration was made, it functioned like it was placed normally. The ESCs control wires were routed through holes in the bottom plate of the frame and plugged into the correct ports in the flight controller. It was important to plug them in the correct order, which is found in the Ardupilot software documentation. In the case of a hexacopter with a cross configuration, the order is "5-1-4-6-2-3", meaning the top right motor plugs into port five, the next motor in a clockwise direction into port one, and so forth. The power cables for the flight controller were also routed from the top side, as they come from the power distribution board. The power distribution board has two power outputs for the flight controller, both completely independent. If one fails, the other will keep sourcing power, avoiding losing drone control.

Figure 4.8: Flight controller's (top) and power distribution board's (bottom) buttons, attached to one of the frame's legs.

The flight controller and power distribution board have activation switches which can be seen in 4.8; the flight controller switch is essentially an "ON/OFF" switch; the flight controller will not function if it is not activated. When the flight controller is initially powered up, this button's LED will be blinking, which means it is is the "OFF" state. Only after pressing it for about one second does it turn solid red, meaning it is in the "ON" state. If wished, the button can be pressed again, returning the flight controller to the "OFF" state. The power distribution board has an "ON/OFF" switch which enables and disables the power supply to the ESCs. When it is blinking green, it means it is OFF; consequently, the ESCs are powerless. It turns solid green when pressed for about one second, and the ESCs receive power, which can be noticed by the motors making a chiming sound. Both of these switches were fixed to one of the legs of the drone, facilitating access and preventing their cables from hitting the propellers.

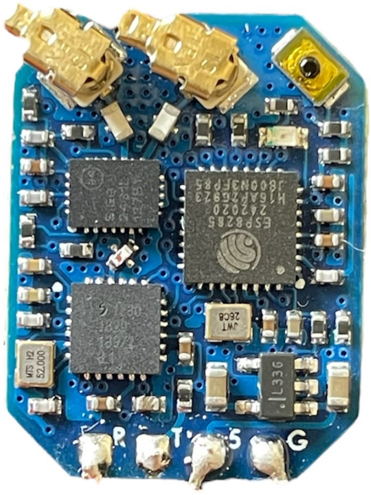


Figure 4.9: The Receiver board. Notice the pins in the bottom, which were already soldered when this picture was taken.

The ELRS receiver came as a PCB without any soldered wires. For the connection to work, it was necessary to solder wires into the PCB, which then connected to the flight controller. The ports, which can be seen in figure 4.9 are "5", "GND", "TX", and "RX"; 5 and GND are related to the power supplied to the board, "5" is for the five volts supply required to run the board, and "GND" is the respective ground. "TX" and "RX" are UART pins for transmitting and receiving data. Because the flight controller comes with several cables, some were unused. Specifically, the cable with the flight controller safety switch has two more outputs, which were both unused. The port these cables plug into in the flight controller is a UART port, which the ELRS receiver requires. One of the two extra outputs has the four required connections for the receiver to work (5V, GND, TX and RX). This cable was adapted for the ELRS receiver; the output port was cut off, exposing the metal cables. A small part of the protective rubber casing was removed, further exposing more metal required for soldering. The cables were each connected and soldered to the correct port in the ELRS receiver (5V connects to 5V, GND to GND, RX to TX and TX to RX). After plugging it into the powered flight controller, it was verified that the receiver was powered on by its flashing red LED.

Figure 4.10: The GPS after mounting it to the frame. One of the receiver's antennas was attached to it.

The obtained GPS came with a carbon fibre mount for elevating it above the frame. It was mounted in the back of the drone with zip-ties, as there was no place to screw it on. The GPS cable goes through the inside of the mount and exits through its base. It then plugs into the Flight Controller in the CAN port by routing it through the frame plates.

After plugging into the flight controller, some registers had to be altered for it to connect properly. "CAN_D1_PROTOCOL" and "CAN_P1_DRIVER" were set to "1", enabling the port and setting it to "DRONECAN" mode. "GPS_TYPE" was set to "9", which sets the communication protocol type to DRONECAN and finally "NTF_LED_TYPES" was set to 231, which enables the GPS LEDs by setting them to DRONECAN.

After these configurations, the GPS was connected to the flight controller, confirmed by viewing it in Mission Planner; It was initially not functioning, as it required compass required calibration. This calibration had to be done outside, as a GPS lock was required. The calibration is done by moving the drone in its three axes until Mission Planner confirms the calibration is done. After the calibration, the GPS could function properly; it could be seen as giving off a position near where the drone was truly situated. The GPS also featured LEDs that communicated the current state of the drone; for example, a flashing blue means disarmed with no GPS lock, and solid blue means armed with no GPS lock. The full list of states can be consulted in the component's documentation.

Figure 4.11: The finished, complete build, missing only the propellers.

The finished first iteration of the build can be seen in 4.11. The drone weighed 2219 grams without the batteries attached. The batteries weighed 2188 grams. In total, it weighed 4407 grams.

4.2 Software Setup

The "Mission Planner" software was installed on a portable computer. This piece of software was critical for the drone setup, as it is responsible for installing the software that controls the drone, configuring everything needed, and assuring connection between all the components. A USB-A to micro-USB cable connected the laptop and Mission Planner to the Cube Orange+ Flight Controller. This connection was used several times throughout the build process, as Mission Planner is necessary for every calibration and configuration.

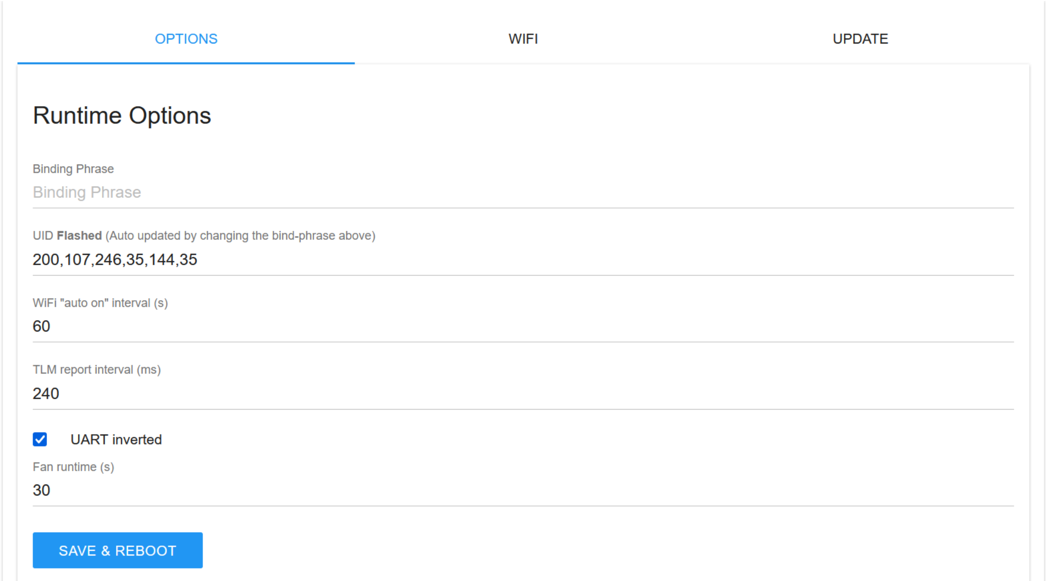
After establishing this physical connection, ArduCopter for hexacopters was installed into the Controller through Mission Planner's firmware install feature. Only after installing ArduPilot, could we establish a permanent link to the Controller through Mission Planner.

Figure 4.12: Before and after the connection to the Flight Controller was established.

Figure 4.12 shows the different connectivity states to the Flight Controller. After the connection is established, several options appear in Mission Planner.

It was first recommended to calibrate and configure the Flight controller. The first configuration to choose is the frame type, which is of the cross type in our case. After this, the accelerometer was calibrated by placing the flight controller on every one of its edges. The compass was calibrated by rotating the flight controller in its three axes. The Flight Controller software warned the user when the calibration was done.

The flight controller outputs for controlling the ESCs were mapped inside Mission Planner. There are fourteen outputs, eight main outputs and six auxiliaries. These outputs are responsible for controlling the motor's ESCs; because we have six ESCs, six outputs will be used. The first six main outputs were used, as they were the most convenient to use with the flight controller location in mind. There is an option for calibrating ESCs, but the manufacturer indicates they come pre-calibrated, which will be tested later.



Runtime Options

Binding Phrase
Binding Phrase

UID **Flashed** (Auto updated by changing the bind-phrase above)
200,107,246,35,144,35

WiFi "auto on" interval (s)
60

TLM report interval (ms)
240

☑ UART inverted

Fan runtime (s)
30

Figure 4.13: The ELRS configuration webpage for the radio transmitter.

The connected ELRS receiver did not automatically connect to the radio controller because it was not in binding mode (it is not searching to connect to any remote). The fastest way to bind it to our remote controller would have been to power the receiver on and off three times rapidly, setting it into binding mode and then putting the remote into binding mode. However, after many tries, this method would not work. This was not a serious problem, as the recommended method by the firmware developer for binding the remote to the receiver is a different one. The receiver and transmitter have Wi-Fi capabilities, allowing wireless configuration: When the receiver has been on for more than 60 seconds and does not bind, it will go into Wi-Fi mode. A wireless network named "ExpressLRS RX" will be created with the password "expresslrs". This wireless network does not have access to the internet; however, it does have access to some important configurations in the receiver when accessing the "10.0.0.1" IP through a web browser, of which an example can be seen in 4.13. One of the configurations is the "Binding phrase". This binding phrase can be any phrase the user wishes. If both a receiver and transmitter have the same binding phrase and are within range of each other, they will automatically bind as soon as they are turned on. A similar procedure can be done in the transmitter (remote controller).

```
RadioMstr TX16S                                   0/250
Packet Rate              250Hz(-108dBm)
Telem Ratio              1:8 (1171bps)
Switch Mode              Wide
Model Match              Off (ID: 0)
> TX Power (100mW)
> VTX Administrator
> WiFi Connectivity
> Backpack
 [BLE Joystick]
 [Bind]
3.1.2 CE_LBT             4da3aa
```

Figure 4.14: The ELRS Lua script used for configurating the ELRS module in the remote controller.

An ELRS LUA script came preloaded with the remote controller, as it has an integrated ELRS transmitter; this script can be seen in figure 4.14 and it permits changing some settings, making the receiver go into the traditional binding mode, and enabling Wi-Fi on the controller, creating a wireless network named "ExpressLRS TX" with the password "expresslrs". A page similar to the receiver can be accessed, and a "Binding phrase" can also be chosen.

As said above, f both a receiver and transmitter have the same binding phrase and are within range of each other, they will automatically bind to each other. After our transmitter and receiver were configured to have the same binding phrase and turned on, the receiver's LED turned solid red, signifying an established connection.

The connection was confirmed as working in Mission Planner's Radio Calibration: The remote controller's inputs clearly showed on the screen.

Some configurations were made in the controller operating system. The first step was calibrating the joysticks and buttons; this calibration was done by bringing every joystick and button to their extremes. A model was configured specially for the created hexacopter. This model was configured to have the "SF" button as the arming switch and the "SA" button as the mode switch. The arm button is a two-position switch, with the up position being "disarmed" and the down position being "armed". The ELRS protocol mandates that this switch be the arming switch, and it is convenient because it is the only normal two-positon switch in the remote controller. The remote was configured to output a sound saying "armed" when the button is switched to armed and "disarmed" when switched to disarmed. The mode button is a three-position switch configured similarly to the arming button. There is also sound playing when switching between modes, but the modes depend on user configuration in Mission Planner and are altered depending on the current mission.

Figure 4.15: The remote controller after setup.

The above figure 4.15 shows the main screen of the controller after the full configuration.

After these configurations, it was necessary to do a Remote Controller calibration in Mission planner. This calibration is done similarly to the controller's calibration referred to above; however, it is done in the Mission Planner application so that the flight controller can register the minimum and maximum outputted values.

4.3 Build testing

After making the required connections (battery, PDB, ESCs, motors and the controller connected to each other), enabling the power supply by toggling its cut-off button, and turning the Flight Controller on with its button, a "Motor test" was run using the Mission Planner application. This test permits checking one individual motor or all motors and allows us to choose a percentage of speed that the motors will run at and the number of seconds for the motors to run.

For example, considering only one motor is tested, the flight controller buzzer plays three beeps once the test begins, and the motor spins up. After the timer ends, the motor stops, and the buzzer plays three beeps again. If the user wishes, all motors can be run simultaneously or sequentially.

At first, when we tried to test the drone's motors, nothing happened. After checking the program for errors and visualizing the output PWM waves from the Flight controller, everything worked as expected. After some research, it was discovered that the chosen ESCs are bidirectional by default, which was unexpected, as drone ESCs are usually unidirectional. Bidirectionality means thrust goes from -100% to 100% instead of 0 to 100%. -100% is full thrust but in the inverse direction. The flight controller outputted 0% thrust, the ESCs interpreted it as -100%, and when the flight controller outputted 50% thrust, the ESCs interpreted it as 0%. When the flight controller outputted 100% thrust, the ESCs interpreted it as 100%. The program did not know this characteristic, resulting in puzzling behaviour.

As a safety measure, the ESCs can only activate after sensing 0% thrust. This feature is intrinsic to the ESC and comes from the factory. During the tests performed, they never activated. When the Flight Controller is idling (Activated, not armed and no motor tests being performed), Its motor outputs are turned on but outputting a PWM wave equivalent to 0% thrust. However, because the ESCs were configured as bidirectional, they interpreted it as constant -100% thrust and never activated when tests were performed with the recommended 10-15% in Mission Planner because it never sensed 0% thrust.

What confirmed this theory was that this safety measure could be bypassed: by running a test at 50% thrust, the ESC interpreted it as 0% thrust. After this, any performed test resulted in motor spin, as the ESC had already sensed the point of 0% thrust. However, the ESCs still obeyed their bi-directionality.

Because the ESCs come with the programmable firmware "BLHELI_S", it is possible to change this setting. To do this, the Flight Controller was used as a bridge from the program to ESCs. To enable the passthrough configuration, a register in the flight controller was changed; The "SERVO_BLH_AUTO" register was switched from 0 to 1. After closing the Mission Planner's connection to the Flight Controller, a program named "BLHeliSuite" was opened, and a connection was established to the Flight Controller.

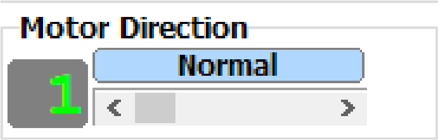

Motor Direction
Normal

Figure 4.16: Motor direction setting inside "BLHeliSuite".

With the ESCs receiving power from the batteries and the connection established, the program can read and write to the ESCs' memory. Only one setting had to be changed; where it can be read in Figure 4.16 "Normal", it used to be read "Bidirectional." Motor tests now ran as expected, and it was verified that all were running without a problem, independently from the applied thrust.

After the remote controller was bound to the receiver and calibrated, it was verified if the drone could be armed and operated without connection to Mission Planner. Without a connection to Mission Planner, the drone was plugged into the batteries, both safety buttons were pressed, and the arming button was switched. The motors spun up to a low rotation speed, which is the expected behaviour, and moving the thrust up made them spin faster. Adjusting roll and pitch made the respective motors spin as expected, confirming that the remote controller and motor wiring were working as expected.

The motors were individually run and checked to see if they were spinning in the correct direction. If they were not, because they are three-phase motors, two of their three cables are switched, which changes the direction of the motor spins.

It was important to verify the flight controller's associated safety features; As a precaution, a test was done to verify if a failsafe was triggered in case of connection loss with the remote controller: with the drone plugged into the battery and armed, the remote controller was turned off. The drone immediately entered failsafe mode, observed in Mission Planner and physically (the motors turned off, and a warning beep was played). With the failsafe verified as working, it could then be configured. It was set to go into "Land" mode if it ever detected a failsafe; the autopilot would stabilize and try to land the drone automatically.

4.4 First flight

After the drone was set up and completely configured, it was time for its first flight. Final checks were done to verify if cables were loose, if every screw was properly tightened, and if the drone was still correctly calibrated.

Figure 4.17: Motor with attached propeller.

The only remaining thing to do before flying was to attach the propellers, which were not yet added for safety reasons. Figure 4.17 shows an arm with a propeller attached.

The test itself went as planned; after takeoff, the drone was flown for about 2 minutes and 30 seconds. The pilot went through several modes, beginning with stabilize, in which the drone stabilised any horizontal movement correctly; then going to altitude hold, which stabilized both horizontal and vertical movement. Finally, loiter mode was tested, which uses the GPS for locking into a position in the air, which also worked as expected; The drone stayed very still, occasionally compensating for any movement created by the wind.

There were occasional wind blows, which moved the drone out of its place, but were quickly compensated by the flight controller.

All throttle, yaw, pitch and roll commands input by the pilot worked as expected, resulting in stable movements in the aircraft.

The only problem detected with the first iteration of the build was the propeller guards; Because the material used in printing them is quite flexible, they were oscillating because of the air moved by the propellers. This created high-pitched sounds, indicating they caused much vibration. This is worrying, as so much vibration is not good for drone control, and the propellers could potentially touch the guards, causing damage.

Concluding, it was a successful first flight, with the drone taking off, accomplishing every normal movement several times, going through all its modes, and landing safely.

Chapter 5

Conclusion and Future Work

Cargo drones have a high potential for several applications in health, agriculture, photography and filmmaking, security, transportation of goods, search and rescue, disaster relief and others. As of now, it is uncommon to see drones in real-world applications, as the technology is underdeveloped and highly regulated; However, the market points towards constant and rapid growth in future years.

The execution of this work was fundamental for a holistic understanding of the individual parts of a drone, its build process, its configuration, and its operation ambient and limits. Ardupilot, the software used for controlling and configuring the drone, was critical in this learning process, as it is an intuitive framework with documentation backing it up. The final build was capable of performing the previously set objectives.

Regarding future work, the build would first benefit from a better and more updated frame. The one that was obtained is functional for prototyping; However, a bigger frame, capable of taking bigger components, with more cable management options and carbon fibre tube arms, would be highly beneficial for the project. Because of the high weight carried in batteries and payload, the landing gear, both in the current and perhaps in the new frame, would have to be adapted to have higher resistance to strong impacts when landing or even crashing. The propeller guards should be recreated from scratch to be adapted to this multicopter. They should be printed in a more resistant, less flexible material like carbon fibre.

Regarding the controller, the option for reading the amperage passing through the power distribution board was available but not implemented, which should be explored in the future. Even though the performed tests showed the drone was stable and possible to control, there is always room for adjusting and improving the control parameters, which can be initially adjusted by the software's autotune feature and further manually.

A system would have to be researched and created for functioning inside an indoor space, perhaps using a combination of sensors and cameras in the drone body like the ones explored in the state-of-the-art. Depending on the type of indoor space where the system would be implemented, it could also benefit from adapting the space to drones flying indoors; as it was noted in the state-of-the-art, it is not an easy task for computer vision to function indoors due to the particularity and complexity of these spaces; Markers could be implemented in difficult-to-see obstacles. Furthermore, an indoor positioning system could be implemented to give the controller accurate positioning data and consequently avoid most computer vision complexities.

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