МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ
НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ
Факультет аеронавігації, електроніки та телекомунікацій
Кафедра авіаційних комп’ютерно-інтегрованих комплексів

ДОПУСТИТИ ДО ЗАХИСТУ
Завідувач випускової кафедри
________ Віктор СИНЄГЛАЗОВ
“___”_______________2024 р.

КВАЛІФІКАЦІЙНА РОБОТА (ПОЯСНЮВАЛЬНА ЗАПИСКА)

ВИПУСКНИКА ОСВІТНЬОГО СТУПЕНЯ

“БАКАЛАВР”

Спеціальність 151 «Автоматизація та компю’терно-інтегровані технології»
Освітньо-професійна програма «Комп’ютерно-інтегровані технологічні процеси і виробництва»

Тема: Робототехнічний комплекс доставки вантажів

Виконавець: студент групи КП-402Ба Бондар Павло Юрійович
Керівник: доцент Микола Павлович Василенко

Нормоконтролер: _________ Філяшкін М.К
(підпис)

Київ – 2024

MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE
NATIONAL AVIATION UNIVERSITY
Faculty of Aeronautics, Electronics and Telecommunications
Department of Aviation Computer-Integrated Complexes

PERMISSION TO DEFEND
Head of the department
________ Viktor SINEGLAZOV
“___”_______________2024 р.

QUALIFICATION WORK
(EXPLANATORY NOTE)

GRADUATE OF AN EDUCATIONAL DEGREE

“ BACHELOR”

Speciality 151 «Automation and Computer-Integrated Technologies»
Educational-Professional Program: «Computer-Integrated Technological Processes and Production»

Theme: Robotic cargo delivery complex

Performer: student of the group KP-402Ba Bondar Pavlo Yuriiovych

Supervisor: associate professor Mykola Pavlovych Vasylenko

Normative Controller: _________ Filiashkin M.K
(signature)

Kyiv 2024

НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ

Факультет аеронавігації, електроніки та телекомунікацій
Кафедра авіаційних комп'ютерно-інтегрованих комплексів

Освітній ступінь: бакалавр

Спеціальність 151 «Автоматизація та комп’ютерно-інтегровані технології»

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ЗАТВЕРДЖУЮ
Завідувач кафедри
___________Віктор СІНЕГЛАЗОВ
«___» ___________ 2024 р.

ЗАВДАННЯ

На виконання кваліфікаційної роботи здобувача вищої освіти

Бондара Павла Юрійовича

1. **Тема роботи:** «Робототехнічний комплекс для доставки вантажів».

2. **Термін виконання роботи** з 13.05.2024 р. по 3.06.2024 р.

3. **Вихідні дані до роботи:** Розробка робототехнічного комплексу малої дальності для доставки вантажів в міських умовах.

4. **Зміст пояснювальної записки** (перелік питань, що підлягають розробці):

   1. Аналіз існуючих робототехнічних комплексів для доставки вантажів;
   2. Розробка власного робототехнічного комплексу для доставки вантажів.

5. **Перелік обов’язкового графічного матеріалу:** Презентаційний матеріал представлений у електронному та фізичному форматі який містить процес збору робототехнічного комплексу, його програмування та налаштування, блок схему будови комплексу.

6. **Календарний план-графік**

№ п/п	Завдання	Термін виконання	Відмітка про виконнання
1.	Отримання завдання	13.05.2024 - 13.05.2024	
2.	Формування мети та основних завдань дослідження	13.05.2024-14.05.2024	
3.	Аналіз існуючих комплексів	14.05.2024-17.05.2024	
4.	Розробка структурної схеми комплексу	17.05.2024-20.05.2024	
5.	Підбір компонентів	20.05.2024-22.05.2024	
6.	Збірка та налаштування	22.05.2024-28.05.2024	
7.	Програмування комплексу для виконання місій доставки	28.05.2024-3.06.2024	

7. **Дата видачі завдання** “13” травня 2023

Керівник: ____________________________ Микола ВАСИЛЕНКО

Завдання прийняв до виконання ________________________ Павло БОНДАР

NATIONAL AVIATION UNIVERSITY

Faculty of Air Navigation, Electronics and Telecommunications

Department of Aviation Computer-Integrated Complexes

Education level: bachelor

Speciality: 151 "Automation and Computer-Integrated Technologies"

Educational and Professional Program: "Computer-Integrated Technological Processes and Production"

APPROVED
Head of Department
_________Viktor SINEGLAZOV
«___» ___________ 2024 р.

TASK

For the student`s thesis

BONDAR PAVLO YURIYOVYCH

1. **Theme of the project::** "Robotic cargo delivery complex".
2. **Term of work performance:** from 13.05.2024 to 3.06.2024.
3. **Output data to the project (work):** Development of a short-range robotic complex for cargo delivery in urban conditions.
4. **Contents of the explanatory note (list of questions to be developed):**
    1. Analysis of existing robotic complexes for cargo delivery;
    2. Development of our own robotic complex for cargo delivery.
5. **List of compulsory graphic material:** Presentation material presented in electronic and physical format, which includes the process of assembling the robotic complex, its programming and setup, a block diagram of the complex structure.

6. **Planned schedule:**

№	Task	Execution term	Execution mark
1.	Task receiving	13.05.2024 - 13.05.2024	
2.	Purpose formation and describing the main research tasks	13.05.2024-14.05.2024	
3.	Analysis of existing complexes	14.05.2024-17.05.2024	
4.	Development of a structural diagram of the complex	17.05.2024-20.05.2024	
5.	Selection of components	20.05.2024-22.05.2024	
6.	Assembly and configuration	22.05.2024-28.05.2024	
7.	Programming the complex for delivery missions	28.05.2024-3.06.2024	

7. **Date of task receiving:** “13” may 2023

Diploma thesis supervisor: ____________________________ Mykola VASYLENKO

Issued task accepted ________________________ Pavlo BONDAR

РЕФЕРАТ

Пояснювальна записка кваліфікаційної роботи бакалавра «Робототехнічний комплекс для доставки вантажів» 87 с., 41 рис., 3 табл., 13 джерел

Об'єкт дослідження - Дана кваліфікаційна робота присвячена розробці комплексу для доставки вантажів.

Мета кваліфікаційної роботи - Розробка та дослідження робототехнічного комплексу для автоматизованого транспортування вантажів.

В роботі був виконаний аналіз літератур та існуючих рішень в сфері робототехнічних комплексів доставки вантажів, їх переваг та недоліків,
також була проведенна розробка математичних моделей для моделювання роботи робототехнічного комплексу. Після розробки математичної моделі був виконаний підбір необхідних компонентів та їх поєтапна збірка, після якої було проведено налаштування та програмування робототехнічного комплексу.

Результати роботи можуть бути використані для проектування нових робототехнічних комплексів для доставки вантажу.

У процесі роботи налаштування робототехнічного комплексу здійснювалось за допомогою таких комп'ютерних програм як: PX4 Autopilot та OpenTX firmware.

РОБОТОТЕХНІЧНИЙ КОМПЛЕКС, ДРОН, ДОСТАВКА ВАНАТЖІВ, РОЗРОБКА, ЛОГІСТИКА, МОДЕЛЮВАННЯ

ABSTRACT

Bachelor's Degree Explanatory Note on the Thesis «Robotic cargo delivery complex» 87 p., 41 fig., 3 tab., 13 ref.

Object of study - This qualification work is devoted to the development of a complex for the delivery of cargo.

Purpose of the qualification work - Development and research of a robotic complex for automated cargo transportation.

The work analyzed the literature and existing solutions in the field of robotic cargo delivery systems, their advantages and disadvantages, and developed mathematical models for modeling the operation of the robotic system. After the development of the mathematical model, the necessary components were selected and assembled in stages, after which the robotic complex was configured and programmed.

The results of the work can be used to design new robotic systems for cargo delivery.

In the course of work, the robotic complex was configured using such computer programs as: PX4 Autopilot and OpenTX firmware.

ROBOTIC COMPLEX, DRONE, CARGO DELIVERY, DEVELOPMENT, LOGISTICS, MODELING

CONTENT

LIST OF TERMS

ESC - Electronic speed controllers

PDB - Power Distribution Board

GPS - Global Positioning System

UAV - Unmanned aerial vehicle

VTOL - Vertical Take-Off and Landing

FPV - First-person view

FOV - Field of view

LiDAR - Light Identification, Detection and Ranging

GNSS - Global Navigation Satellite System

IMU - Inertial measuring device

UV - Ultraviolet cameras

PID - Proportional–integral–derivative

PWM - Pulse-width modulation

PCB - Printed circuit board

INTRODUCTION

The transportation sector, like all sectors of the economy, is subject to the impact of successive technological revolutions experienced by humanity. The invention of the steam engine, the automobile, or the airplane had a significant impact. The advent of drones will not go unnoticed, and it can even be said that the changes they will bring to our lives will be more significant than those previously brought about by other inventions.

In my work I will focus on unmanned aerial vehicles (UAVs), excluding ground-based ones due to their small application area and low number of advantages.

While drones themselves are essential components, they form just one part of a complex, multifaceted delivery system. Unlike manned aviation, unmanned aerial vehicles (UAVs) require additional system support elements. These include the drone itself, the operator's workstation, software, data transmission links, and the elements necessary to execute the delivery.

For a long time, drones have been seen as a useful means of transportation that allows meeting a wide range of logistics needs and opens up new possibilities for delivering anything, anywhere.

The objective of work was To analyze existing drones and create a cargo delivery drone for logistics optimization, expedited cargo delivery, and mass implementation.

CHAPTER 1

BENEFITS AND POTENTIAL APPLICATIONS OF DELIVERY DRONES

The adoption of drones in the delivery sector currently faces several technical and organizational hurdles that hinder their stable and widespread use. The primary challenges revolve around airspace utilization, frequency spectrum allocation for UAV control and data transmission, and the development of the nascent civil services market.

The impetus for the development of unmanned aviation worldwide stems from the need for lightweight, relatively inexpensive aircraft that possess high maneuverability and the capability to perform reliable deliveries.

At present, parcel delivery drones are mainly available to large companies with sufficient resources to finance their deployment and operation. This limits competition and the ability of new players to enter the drone delivery market. Despite this, many countries continue to invest heavily in the development of this field.

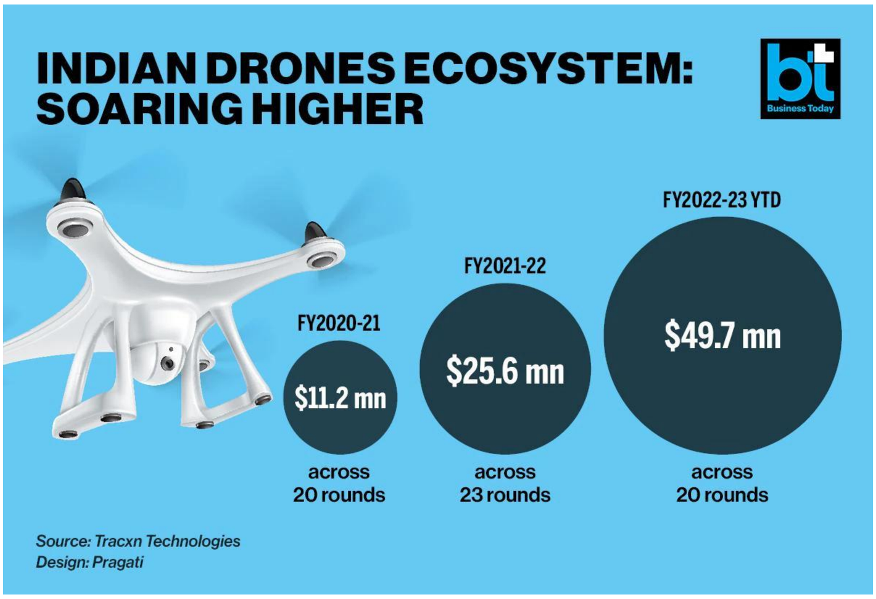
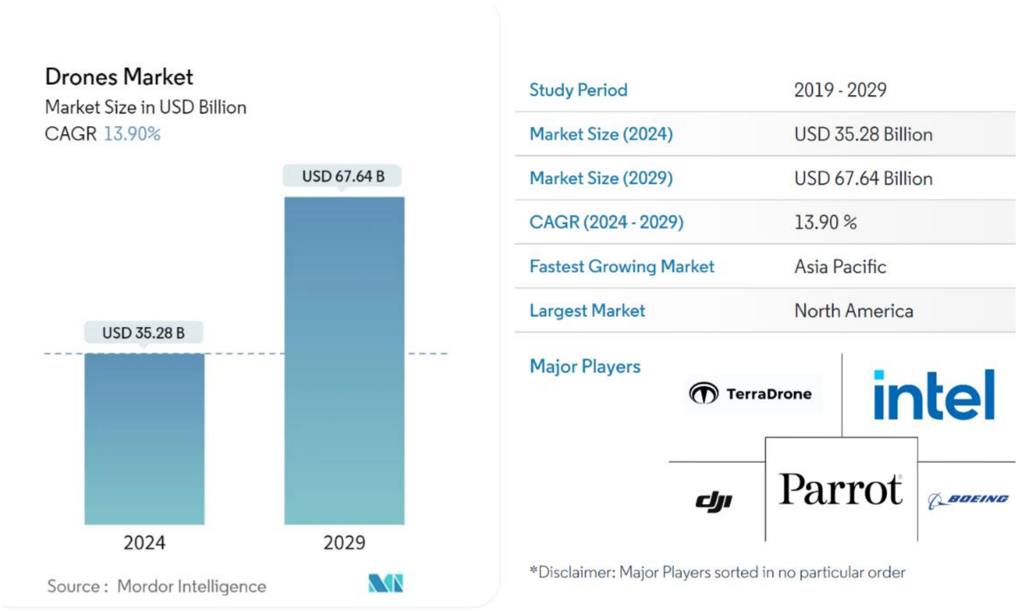


Fig. 1.1 Indian drone industry investments

As evident from Fig. 1.1, the Indian drone industry is experiencing rapid growth, with investments tripling in the past three years. [1]



Study Period	2019 - 2029
Market Size (2024)	USD 35.28 Billion
Market Size (2029)	USD 67.64 Billion
CAGR (2024 - 2029)	13.90 %
Fastest Growing Market	Asia Pacific
Largest Market	North America
Major Players	TerraDrone intel dji Parrot BOEING

*Disclaimer: Major Players sorted in no particular order

Fig. 1.2 US drone industry investments

Analyzing Fig. 1.2 allows us to evaluate investor sentiment and forecast for the drone industry in the US. [2]

Both the Indian and North American drone industries have a promising future. The Indian industry is experiencing rapid growth and is attractive to investors, while the North American industry is more mature and has a wider range of applications. Both regions are expected to see continued growth in the drone market in the coming years.

This suggests that the relevance of drones will only grow and develop in the near future, and new technologies and solutions to pressing problems will emerge.

With the development of technology, the cost of drones and related services is expected to decrease. Improvements in production processes, optimization of components, increased production scale and market competition are contributing to lower drone prices. In addition, the development of new technologies such as lightweight and efficient batteries, autonomous control systems and unmanned technologies can improve the functionality of drones and reduce their operating costs.

It is predicted that with increasing competition and innovation in the market, the cost of drone delivery will become more affordable for various businesses, including small businesses and startups. This will allow to expand the use of drones in logistics and delivery, increasing efficiency and reducing overall delivery costs.

The introduction and use of unmanned aerial vehicles in the commercial sector has provided companies with more opportunities to operate, but has also revealed many disadvantages and challenges that must be overcome.

1.1 Potential applications of drones in cargo delivery:

In E-commerce: Drones could become an indispensable tool for fast and efficient delivery of goods ordered online, especially for urgent or heavy items.
In medical Services:

– Medication delivery: Drones can deliver medications to patients in remote areas or to people who are unable to leave their homes.

– Blood sample delivery: Drones can quickly and safely transport blood samples from hospitals to laboratories, which can expedite diagnosis.

– Medical supplies delivery: Drones can deliver blood, organs, and other medical supplies to hospitals, especially in emergency situations.

In Agriculture:

– Field spraying: Drones can be used to spray fields with pesticides and fertilizers more precisely and efficiently than ground-based methods, potentially reducing chemical use and increasing crop yields.

– Food delivery: Drones can be used to deliver fresh produce from farms to markets or directly to consumers, which can reduce spoilage and improve product quality.

In Construction**:**

– Materials delivery: Drones can deliver materials to heights, potentially improving construction efficiency and safety, but limited to small and lightweight items for now.Cargo delivery by drones has immense potential to revolutionize many industries. However, several challenges need to be addressed before this technology can be widely adopted.

1.2 Limitations and Challenges:

– Safety: Strict regulations and protocols need to be established to ensure the safe operation of drones, especially in proximity to people and infrastructure.

– Privacy: Data collection and usage by drones must adhere to stringent privacy regulations.

– Infrastructure: Adequate infrastructure, including charging stations, air traffic control systems, and maintenance facilities, is required to support widespread drone usage.

– Public perception: Concerns regarding safety, privacy, and noise associated with drone operation need to be addressed.

Having explored the potential applications and limitations of drones, we raise the pivotal question: Does their implementation merit pursuit? To answer, we need to know the pros and cons of using drones for delivery.

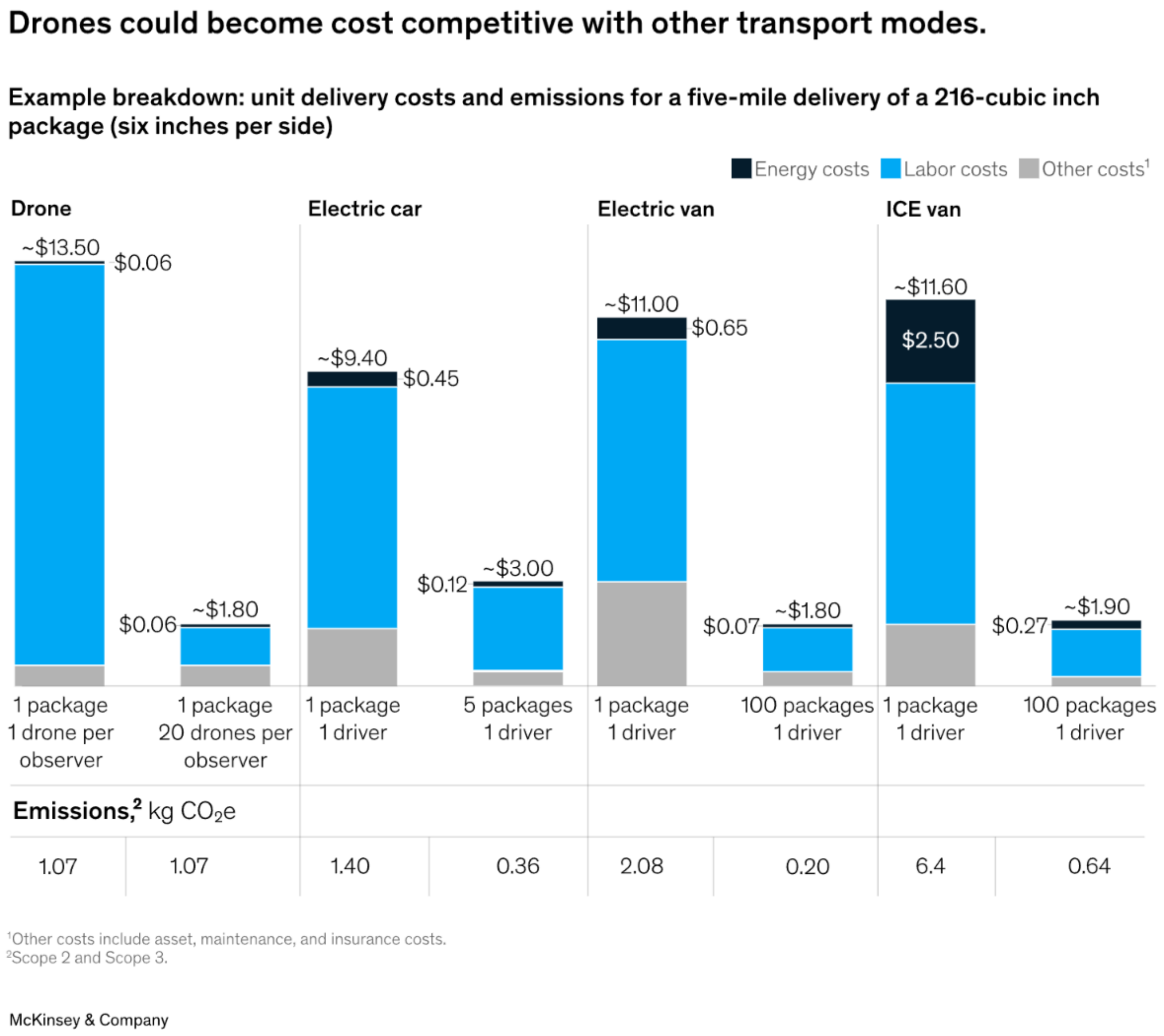
1.3 Advantages of Using Drones for Transportation

Drones' flexibility makes them highly versatile, enabling their integration with traditional vehicles into transportation fleets and distribution processes. While drones cannot fully replace all modes of transport due to their current limitations (range and weight restrictions), they can enhance logistics and make it more efficient. This combination will ultimately become essential for improving delivery services and compensating for drones' shortcomings in cargo transportation. Therefore, the advantages that drones bring to transportation are evident and can be summarized as follows:

– Significant reduction in distribution costs

Drones' efficiency stems from their electric motors, which consume significantly less energy compared to traditional internal combustion engine-powered vehicles. This makes drones more energy-efficient, leading to lower fuel costs.

Furthermore, using drones can reduce expenses on other modes of transport, such as vans, trucks, and motorcycles, typically used for short-distance deliveries. Drones can perform "last-mile delivery" more effectively and economically, freeing up larger and more expensive vehicles for longer or bulkier hauls.


Drones could become cost competitive with other transport modes.

Example breakdown: unit delivery costs and emissions for a five-mile delivery of a 216-cubic inch package (six inches per side)

¹Other costs include asset, maintenance, and insurance costs.
²Scope 2 and Scope 3.

McKinsey & Company

Fig. 1.3 Drone unit delivery costs and emissions compared to other vehicles

By analyzing Fig. 1.3, we can conclude that drones are not for single packages, but ideal for wholesale. [3]

At the moment, a drone is not the optimal choice for single parcel delivery because It is more expensive to deliver a single parcel with a drone than with an electric car, electric van, or even an internal combustion engine van. Most drones cannot carry heavy or large items, which limits their use.

However, when delivering 100 parcels or more, a drone becomes a viable option. The price of shipping a single parcel by drone is significantly reduced for bulk orders. Drones can fly directly to the destination, bypassing traffic jams and other obstacles for fast delivery. Today, drones are already capable of wholesale delivery, but with certain limitations due to battery capacity and weight carried.

Additionally, drones' autonomy allows them to operate without constant human control. Unlike traditional vehicles, drones don't require a driver on board. Instead, they can be remotely controlled by a pilot using specialized software and control systems. This decreases labor and maintenance costs as fewer personnel are needed to operate drones.

However, it's worth noting that even with autonomous drone operation, professional personnel are still required for management and oversight. Drone pilots typically undergo specialized training and certification to ensure safe and effective operation of unmanned aerial vehicles.

– Risk mitigation

A crucial aspect of using drones in such scenarios is their ability to deliver aid without risking the lives of pilots or other rescue workers. Due to their unmanned navigation and autonomy, drones can function even in complex and hazardous conditions, completely eliminating human risk.

– Environmental friendliness

Drones' eco-friendliness is an important aspect of their use in transportation and delivery. The primary factor making drones more environmentally friendly is their electric propulsion. As most drones operate on electric motors, they do not emit harmful gases and waste products into the environment, reducing their ecological footprint compared to traditional gasoline or diesel-powered vehicles.

Referring to Fig. 1.3 we can say that drones are twice as environmentally friendly as other forms of transportation and produce almost no exhaust gasses, making them a more environmentally friendly mode of transport compared to combustion engine vans.

Additionally, drones typically have small sizes and weights, which further contribute to their eco-efficiency. Their use can reduce the need for large and heavy vehicles for delivering small-volume goods, leading to reduced energy consumption and emissions.

Drones also promote route optimization for deliveries, which can minimize fuel and time expenditures, further reducing environmental impact. They can deliver goods directly to their destinations, minimizing unnecessary travel and resource consumption.

– Ability to deliver to remote and inaccessible areas

Drones' capability to fly and navigate complex terrain makes them ideal for delivering goods to remote or inaccessible areas where traditional vehicles have limited access or are unable to deliver due to challenging conditions. This advantage is particularly valuable for last-mile delivery, where goods need to be delivered directly to the end recipient, even if the location is in remote or difficult-to-reach areas.

Drones can easily overcome challenging terrain obstacles such as mountainous landscapes, forested areas, or water bodies that may hinder the movement of traditional vehicles. This makes deliveries possible to remote regions or locations where roads are nonexistent or impassable.

Additionally, drones can operate in low-visibility or adverse weather conditions when other transportation modes may be hindered or unable to take on routes. This allows deliveries to continue regardless of fluctuating weather conditions.

Utilizing drones for delivery enables companies to expand their reach and ensure deliveries to areas that were previously deemed challenging or impossible. This opens up new possibilities for logistics operations and enhances customer service levels, making this technology a crucial component of modern logistics.

– Reduced delivery times, especially for quick or urgent deliveries

This stems from drones' ability to fly through the air, bypassing traffic congestion and delays that often slow down traditional road-based vehicles.

Drones can provide a more direct and efficient delivery route, making them an ideal choice for urgent orders or time-sensitive deliveries. They can also seamlessly integrate with other modes of transport, such as trucks or vans, for more streamlined and rapid deliveries.

By avoiding traffic jams and being independent of road infrastructure, drones significantly reduce order delivery times, improving overall delivery service and enhancing customer satisfaction. This aspect becomes particularly crucial in e-commerce and urgent delivery settings, where delivery time plays a decisive role for customers.

Imagine a scenario where you order a last-minute birthday present and receive it within the hour, all thanks to a buzzing drone zipping through the sky.

Here's a breakdown of how drone delivery stacks up against traditional truck delivery, specifically focusing on rush hour traffic in a city center:

– Reduced traffic congestion in cities

A major contributor to urban traffic congestion is the number of trucks and vans used for goods delivery on city streets. Traditional vehicles, such as trucks, can create bottlenecks and lead to road congestion.

Substituting a portion of transportation with drones can reduce the number of trucks on roads. Drones can deliver goods directly to their destinations, bypassing traffic jams and not adding further congestion to city streets. This is particularly relevant for short-distance deliveries within a city or district.

Reducing traffic congestion has several positive effects on urban infrastructure and the environment. It can lower air pollution and noise levels, improve road safety, and make the urban environment more comfortable for residents and pedestrians.

Thus, using drones for goods delivery not only enhances the efficiency of logistics operations but also contributes to improving the urban environment by reducing traffic congestion and its associated problems.

The advantages of using drones are plentiful, especially since these advantages are currently irreplaceable. There is no other way to eliminate the risk to humans and increase the speed and efficiency of delivery other than using drones. But everything has its drawbacks, which we will now discuss.

1.4 Disadvantages of using drones for delivery

While the advantages of drone delivery outweigh the disadvantages, the latter still exist and can be summarized as follows:

– High cost of the technology.

Unfortunately, the high cost of drone technology is a significant barrier to its widespread adoption in the delivery industry. This includes not only the cost of the drone itself but also the costs of software development, personnel training, security, and logistics management. All of these factors make drone delivery unaffordable for many small and medium-sized businesses that find it difficult to justify such a high investment.

– The lack of a human factor

The lack of a human factor is both an advantage and a disadvantage when using drones for transportation and delivery. The ability to fully automate the delivery of goods ensures the efficiency and reliability of the process, however, certain limitations and risks arise.

One of the main drawbacks of the lack of a human factor is the limited ability of drones to adapt to unexpected situations or changes in delivery tasks. Drones follow a strictly defined algorithm and program, which makes them vulnerable to unforeseen problems or situations. For example, if the recipient's address was entered incorrectly or changed at the last minute, the drone cannot make its own decision and adjust the delivery route, as a human courier can.

In addition, drones cannot make decisions based on personal experience or intuition, which makes them less flexible compared to human couriers. For example, a drone cannot assess the situation on the ground to determine a safe landing spot or the best way to deliver in a particular situation.

Another drawback is the vulnerability of drones to external influences or third-party interference. Since drones can be hacked or manipulated, there is a potential risk of theft or cargo theft. Without a human presence to ensure the safety and security of the cargo, drones can become targets for criminal activity.

To address these issues, additional technologies and security measures need to be developed and implemented. This includes developing smarter and more autonomous drone control systems, as well as using secure encryption and identification algorithms to prevent hacking and unauthorized access.

Thus, the lack of a human factor represents a complex balance between efficiency and risk when using drones for transportation and delivery. Further innovation in technology and security can help reduce these risks and make drone delivery more reliable and widely applicable.

– Limited payload capacity at present.

Limited payload capacity means that drones can only carry small cargo or parcels, often within a few kilograms. This limitation has a significant impact on the use of drones in business and industry, where the transport of larger or heavier items is required.

One of the reasons for the limited payload capacity is the technical complexity of creating and maintaining unmanned aerial vehicles (UAVs) with higher payload capacity. Larger drones capable of carrying heavier payloads require more powerful motors, more power, and stronger structures, which can increase the weight and cost of the device. Additionally, increasing payload capacity can increase the risks of air accidents and create additional safety requirements.

Nevertheless, research and development in the field of drones is ongoing, and engineers are working on new technologies and materials that can improve the payload capacity of drones in the future. It is expected that with the development of new materials, batteries and control systems, the payload capacity of drones will increase, making them more useful for a wider range of applications, including courier delivery, logistics and infrastructure work.

– Weather conditions.

Another significant drawback of using drones for transportation is their vulnerability to weather conditions. Weather can have a significant impact on the ability of drones to perform their tasks safely and effectively.

Wind, rain, snow, fog, and other atmospheric conditions can create obstacles for drone flight. Strong winds can affect the flight stability and controllability of the drone, especially reducing its accuracy in delivering goods. Rain and snow can negatively affect the electronics and mechanics of the drone, which can lead to malfunctions or loss of control. Fog and poor visibility can make it difficult to navigate and detect obstacles, increasing the risk of accidents.

The safety of drone flight in bad weather conditions becomes a critical aspect. To ensure the safety and reliability of delivery in various weather conditions, it is necessary to develop special control algorithms, take into account atmospheric data, and terrain features.

Various approaches and technologies can be used to overcome weather-related limitations. For example, drones can be equipped with more advanced stabilization and wind compensation systems, as well as sensors capable of detecting and avoiding obstacles in real time. It is also important to develop safety protocols and standards for drone operation in various weather conditions.

However, despite technological advancements, weather conditions remain a significant factor affecting the efficiency and reliability of drone delivery. Working in different climatic zones and seasonal changes may require additional investment in development and testing to ensure stable drone operation in any conditions.

– Limited autonomy.

The limited autonomy of drones, that is, the time a drone can spend in the air without recharging or replacing batteries, is a significant limitation for their use in transportation, especially over long distances.

Currently, most commercial drones have a limited flight time. This limitation is determined by battery capacity, energy efficiency, and drone weight. Thus, even modern lightweight and compact batteries limit flight range and duration.

Because of this limitation, drones can be effectively used for local transportation or short-distance delivery, but cannot perform longer or longer hauls. This makes them a limited tool for delivery to rural or remote areas where distances can be significant.

Developers are actively working to increase the autonomy of drones. New technologies, such as more efficient batteries, improved energy management systems, and optimized drone designs, are aimed at increasing flight time and delivery range. However, achieving autonomy that allows drones to carry out long-haul transportation over significant distances remains a technical challenge for now.

– Regulatory limitations.

Regulatory limitations are a serious factor affecting the use of drones for transportation, especially in urban and populated areas. Despite the potential benefits associated with delivery and logistics, drones are still considered dangerous types of aircraft, and their operational use is regulated by legislation and safety regulations.

One of the main aspects of regulatory limitations is related to safety. Drones can pose a potential hazard to pedestrians, vehicles, and buildings, especially in densely populated areas. Therefore, many countries and regions impose restrictions on the places and conditions of drone use, prohibiting their flights over people or near buildings.

In addition, regulatory limitations also affect privacy and data protection aspects. Drones equipped with cameras or other sensors can raise concerns about privacy violations or misuse of collected data. In many jurisdictions, there are rules and restrictions on the use of drones for collecting and transmitting information.

To overcome regulatory limitations, appropriate safety and regulatory standards need to be developed and implemented. This includes pilot training, licensing and permits for drone operation, as well as the development of technologies and safety systems to prevent accidents.

Thus, regulatory limitations pose a significant barrier to the widespread use of drones for transportation and delivery. Addressing this issue requires a concerted effort from governments, regulators and industry to develop effective and safe frameworks for the use of drones in civilian applications.

Cargo transportation by drones will not begin until technology and field testing demonstrate a high degree of safety and reliability.

Chapter 1 conclusion

In conclusion, the use of drones in the transportation industry is a promising area that can significantly improve the efficiency and cost of delivery.

Cargo delivery by drones has the potential to revolutionize many industries. However, there are a number of challenges that need to be addressed before this technology can be widely adopted.

Continuous research and development is needed to improve drone technologies, including increasing payload capacity, autonomy, flight range, and reliability.

Collaboration between stakeholders: Government agencies, the private sector, research institutions, and the public need to work together to develop the rules, standards, and infrastructure needed for the safe and effective use of drones.

Ethical considerations: Careful consideration should be given to the ethical implications of using drones, such as issues of warfare, surveillance, and the potential for misuse of this technology.

Overall, cargo delivery by drones is an exciting new technology with the potential to change the world for the better. With careful planning, responsible development, and cooperation, we can realize the benefits of this technology while addressing the challenges that come with it.

To do this, we will move on to a comparison of existing drone models. This will allow us to identify differences in functionality and delivery efficiency, which can be key to choosing the optimal solution for specific logistics needs.

CHAPTER 2

TYPES OF DRONES THEIR STRUCTURE. RESEARCH AND COMPARISON OF DELIVERY DRONES.

Before diving into the fascinating world of drone structures and comparing specific delivery models, let's establish a clear classification system. This will help us understand the strengths and weaknesses of different drone types in the context of delivery.

2.1 Drone classification

1) By the type of control system, it can be classified as:
remotely piloted; remotely controlled; automatic; remotely controlled by aviation system.

– Remotely Piloted - controlled directly by the operator within line of sight through a ground station.

– Remotely Controlled - operate autonomously but can potentially be controlled by a pilot or operator, using only feedback, through other control subsystems.

– Automatic - perform pre-programmed actions without pilot control and cannot change the plan of actions during flight or adapt to external changes. However, reusable ones can be reprogrammed before each flight, taking into account changes in the environment and material collected on previous flights.

– Remotely Controlled by Aviation System - perform low-level control by onboard systems or ground station, while high-level control of flight trajectory and/or condition is supervised by the operator.

– Unmanned Automatic - flight is controlled entirely by embedded UAV systems without operator intervention or the use of a ground station, which can be reprogrammed considering changes in the environment or new goals.

2) According to the type of aircraft, UAVs are divided into:
airplane, helicopter and convertoplane. The airplane and helicopter types have the

corresponding appearance and characteristics of the airplane and helicopter, while the convertoplane type combines these two types.

3) According to the type of wing UAVs can be:
fixed wing, fixed wing hybrid VTOL, propellers. Fixed - as a rule, of airplane and helicopter types, using a fixed wing, and floating - used in envelope gliders, having a floating wing.

4) According to the direction of takeoff/landing (method of lift), UAVs can be divided into takeoff and landing directions.

According to the takeoff direction, UAVs are: horizontal, vertical, multi-lift.

By landing direction, UAVs are divided into: horizontal, vertical, parachute, mast, non-landing, multi-lift (using combinations of all types of landing).

The direction and lift depends on the type of wing, also on the ability to take off and land either independently or with the help of auxiliary equipment and/or mechanisms.

5) By takeoff and landing type, UAVs are classified into:
In terms of takeoff, UAVs are: airfield, deck, water, hand-launched, non-typical, multi-takeoff, Catapult Launch.
By landing UAVs are divided into: airfield, spot, deck, water, glider, non-typical, multi-landing.

6) By engine type, UAVs can be: electric, piston , rotary-piston, turboshaft, turboprop, turbojet, turbofan, dual-cycle turbofan, afterburning turbofan, dual-cycle afterburning turbofan, hypersonic ramjet, supersonic ramjet, gas turbine, lift-cruise, ramjet, turbofan with bypass duct, pulse jet, ducted fan, solid rocket, and liquid rocket.

7) By fuel system, UAVs are divided into:

– Single-use (Disposable): These UAVs have a fuel system that is filled once at the factory and cannot be refueled. They are typically used for short-duration missions and are then discarded.

– Multi-use (Reusable): These UAVs have a fuel system that can be refueled multiple times. They are typically used for longer-duration missions and can be reused for multiple flights.
Multi-use UAVs can be further classified by refueling method:

– Ground refueling: These UAVs are refueled on the ground before or after flight.

– Platform refueling: These UAVs are refueled on a platform, such as a ship or another aircraft.

– Air-to-air refueling: These UAVs are refueled in the air by another aircraft.

For example, the ScanEagle UAV is a multi-use UAV that can be refueled on the ground or on a ship.

8) By payload, UAVs can be equipped with: optical cameras, thermal imaging cameras, multispectral cameras, UV cameras, laser scanners, hyperspectral imaging equipment, IR cameras, gyrostabilized gimbals, radars, gas analyzers, and other specialized equipment.

Table 1 - Summary Table by Categories, Weight ,Maximum Range.

Category	Weight (kg)	Maximum range (km)
Nano	Less than 250 grams (0.55 lbs)	Up to 25 kilometers (15.5 miles)
Micro	250 grams to 2 kilograms (0.55 lbs to 4.4 lbs)	Up to 40 kilometers (25 miles)
Small	2 kilograms to 25 kilograms (4.4 lbs to 55 lbs)	Up to 100 kilometers (62 miles)
Medium	25 kilograms to 150 kilograms (55 lbs to 330 lbs)	Up to 500 kilometers (310 miles)
Heavy	More than 150 kilograms (330 lbs)	Up to 2000 kilometers (1240 miles)

2.2 Basic UAV structure

Drones, inspired by the structure of a kite, have a unique design with a single engine positioned diagonally on the body. These aerial machines come down to four key components: the propeller that pushes them forward, the engine providing power, the body that houses everything, and the flight board, the brain of the operation.

There are several types of drones categorized by their physical layout, mainly defined by the distance between their crossed motors. These categories include:

– Single-rotor drones: These are essentially miniaturized helicopters, available in both fuel-powered and electric versions. While the single blade and fuel option offer benefits like increased stability and longer flight times, they also come with higher safety concerns.

– Multicopters: The reigning champions of popularity, these are the smallest, lightest drones readily available. However, their flight distance, speed, altitude capabilities, and payload capacity are all limited.

Within the multicopter category, variations exist based on the number of motors they sport. There are quadcopters with four engines, hexacopters with six, and octocopters with eight. The deciding factor behind this design choice is the drone's carrying capacity and desired operational range.

Tricopters: Offering a cost-effective entry point, tricopters boast VTOL capabilities and exceptional maneuverability across six degrees of freedom (X, Y, and Z axes). However, their asymmetrical design may introduce stability concerns.

Fig. 2.1 Tricopter.

Quadcopters: The reigning workhorse of the drone industry, quadcopters prioritize user-friendliness and versatility with their simple, four-propeller, four-motor configuration. This symmetrical design translates to inherent flight stability. Nevertheless, the absence of redundancy in their motor systems renders them susceptible to complete failure in the event of a single motor malfunction.

Fig. 2.2 Quadcopter.

Hexacopters: Thriving in indoor environments, hexacopters leverage advanced forward vision and ultrasonic sensor suites for precise navigation. Their six-propeller design not only enhances lifting capacity but also introduces redundancy, allowing for continued operation even with a single motor failure. Additionally, features like switchable autonomous and manual flight modes, coupled with extended range capabilities through external control systems, make hexacopters highly adaptable platforms.

Fig. 2.3 Hexacopter.

Octocopters: Representing the pinnacle of multirotor lifting capacity, octocopters boast eight propellers, enabling them to handle a staggering payload. This brute force makes them the undisputed choice for heavy-duty industrial applications.

Fig. 2.4 Octocopter.

Fixed-Wing Drones: Endurance Champions: In stark contrast to their multirotor counterparts, fixed-wing drones rely on airplane-like wings to generate lift. This design paradigm translates to superior efficiency, as minimal energy is expended on maintaining altitude. Consequently, fixed-wing drones boast extended flight times, reaching up to 16 hours or more for gasoline-powered models.

Fig. 2.5 Fixed-Wing Drone.

– Fixed-Wing: The Trade-Off for Long-Range Exploration

While fixed-wing drones excel in long-distance flight times, their operational limitations are crucial to consider.

Drawbacks of Fixed-Wing Drones:

– Limited Maneuverability: Fixed-wing drones lack the ability to hover or fly in one spot like their multirotor counterparts. This necessitates a runway or launcher for takeoff and a designated landing zone, potentially requiring a runway, parachute, or landing net. Only the most compact fixed-wing models can be hand-launched and belly-landed in open areas.

– Complexity and Cost: Operating fixed-wing drones presents a steeper learning curve compared to multirotors. Pilots often require training and certification to develop the necessary skills for takeoff, flight, and smooth landings. Additionally, the cost of fixed-wing drones can be higher due to their more complex design.

– Higher Speed Demands: Fixed-wing drones typically maintain a higher cruising speed than forward-flying multirotors. This can be a disadvantage in scenarios requiring slower, more precise control.

Fixed-Wing Hybrid VTOL: A Marriage of Efficiency and Maneuverability

Emerging as a powerful solution, fixed-wing hybrid VTOL drones bridge the gap between long-range capabilities and operational flexibility. These drones combine the endurance of fixed-wing designs with the vertical takeoff and landing (VTOL) capabilities of rotor-based drones. Imagine a fixed-wing drone equipped with rotors or propellers that can tilt for vertical lift during takeoff and landing, then shift for forward flight. This ingenious design offers the best of both worlds:

– Durability and Efficiency: Fixed-wing hybrid VTOL drones inherit the robust construction and long-range potential of fixed-wing designs.

– Operational Flexibility: By incorporating VTOL technology, these drones eliminate the need for runways or dedicated launch and landing zones, offering greater operational flexibility.

– Evolving Control Systems: Advancements in autopilots, gyroscopes, and accelerometers have simplified the operation of fixed-wing hybrid VTOL drones, making them more accessible to a wider range of users.

Fig. 2.6 Fixed-Wing VTOL drone.

Fixed-wing hybrid VTOL drones offer a compelling blend of capabilities. They can take off and land vertically like multirotors, yet possess the endurance and payload capacity of fixed-wing designs for long-distance heavy-duty missions. However, there's room for optimization in both forward flight efficiency and hover stability. Additionally, the need for specialized personnel to operate these advanced drones remains a factor to consider.

Drones rely on various power sources to take flight, each with its own advantages and limitations. Here's a breakdown of the most common options:

– Battery-powered drones: Lightweight and convenient, these drones offer portability and ease of use. However, their flight times are limited by battery capacity, and frequent recharging can be a constraint. Additionally, batteries degrade over time, requiring replacements.

– Gasoline-powered drones: These drones boast extended flight times due to the high energy density of fuel. They are ideal for heavy lifting and long-range applications. However, drawbacks include noise pollution, the risk of combustion accidents, and the need for special handling due to fuel storage and potential spills.

– Hydrogen fuel cell drones: Emerging as an eco-friendly option, hydrogen fuel cells offer a longer flight time than batteries with a quicker refueling process. However, managing heat generated by the system and achieving optimal operating efficiency remain challenges for this technology.

– Solar drones: Harnessing the power of the sun, solar drones boast low operating costs and quiet operation. Unfortunately, their flight times are severely limited by sunlight availability and weather conditions.

2.3 The core components that give a drone its form and function.

The Drone's Backbone: The Frame

The frame is the core structure of a drone, acting like the skeleton for the entire machine. Similar to a computer's chassis, it houses all the essential components. Imagine the propellers, motors, battery, camera, and receivers neatly fitting into this central body, ready to work together.

The typical design resembles an "X" with four arms extending outwards from a central hub. This central area holds most of the drone's internal components, including rotors, batteries, flight control boards, and cameras. We can even compare the frame to the human skeleton, providing the essential structure for the drone's "body."

Key factors to consider include the availability of spare parts, the balance between affordability and quality, and the overall performance the frame offers.

While pricier, carbon fiber frames are another popular choice. This material offers increased durability and reduces the risk of breakage during crashes.

Fig. 2.7 Drone Frame.

The Engine of Flight: Propellers

Drones rely on propellers, also known as rotors or blades, to generate the lift necessary for takeoff and flight. These come in various shapes, sizes, and materials, each affecting the drone's performance.

Propellers are crucial components, but also one of the most vulnerable. They can be easily damaged due to impacts, wear and tear, or even corrosion during flight. For this reason, regular maintenance and pre-flight checks are essential.

Material matters, most propellers are made of plastic, and two key parameters to consider when choosing replacements are the shaft diameter (where the propeller connects to the motor) and the propeller diameter (the overall size of the blade).

Fig. 2.8 Propellers.

Motors: The Powerhouse of Flight

Drone motors are the fundamental driving force behind a Unmanned Aerial Vehicle's (UAV) ability to achieve flight. These critical components convert electrical energy stored in the battery into rotational motion for the propellers, generating the necessary thrust for takeoff, maneuverability, and stable flight. Due to their vital role in a drone's performance, proper motor selection and maintenance are paramount. Regular cleaning to remove dust and debris is essential to ensure optimal lifespan and trouble-free operation. Additionally, any unusual noises emanating from the motor warrant immediate inspection.

There are two primary types of drone motors used: brushed and brushless. The optimal choice hinges on several factors, including the drone's size, weight capacity, and intended application.

– Brushed DC Motors: These motors offer a simpler and more cost-effective design, making them suitable for lighter drones, especially those targeted towards beginner users.

– Brushless DC Motors: Brushless motors provide superior power, efficiency, and longevity compared to brushed counterparts. This makes them the preferred choice for heavier drones employed in professional applications.

When selecting a drone motor, key considerations include the physical size of the motor, the intended payload capacity, and the desired flight characteristics, particularly speed and agility.

Fig. 2.9 Drone Motor.

The Powerhouse: Drone Batteries

Think of a drone's battery as its beating heart. It's the key component that provides the energy to keep the propellers spinning and the drone flying. These batteries are typically made of lithium polymer or lithium-ion cells.

The number of cells in a drone battery determines its voltage. Each cell provides around 3.7 volts. For lightweight hobbyist drones, a single cell (1s) battery is enough. However, drones needing more power use batteries with 2 or 3 cells (2s or 3s).

While these batteries are fairly durable, they can run out of juice. To ensure uninterrupted flights, it's wise to have spare batteries on hand, just in case. The same goes for propellers.

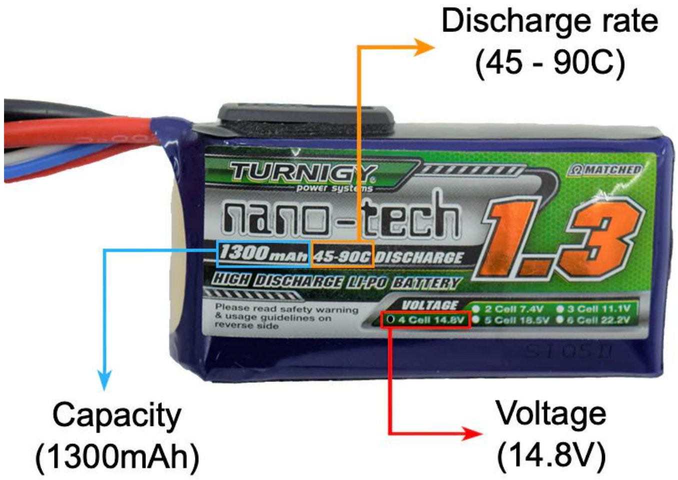


Fig. 2.10 Drone Battery.

The Brain of the Drone: Flight Control Cards

The flight control card is the mastermind behind your drone's movements. Imagine it as the brain, interpreting signals from various sensors and receivers just like nerves. This circuit board uses this sensory information to control the drone.

Think of the sensors as the drone's nervous system. They gather data on things like the drone's tilt, direction, speed, and location (using a gyroscope, magnetometer, accelerometer, and GPS). The flight control card then translates this data into action, adjusting speed, direction, and even activating the camera based on your pre-programmed settings.

This allows the drone to fly smoothly and stably. Some advanced cards even include features like obstacle avoidance to prevent crashes. In fully autonomous drones, the flight control card can handle everything from takeoff (including vertical takeoff or runway launch) to in-flight maneuvers and landing, all following the pre-defined flight plan.

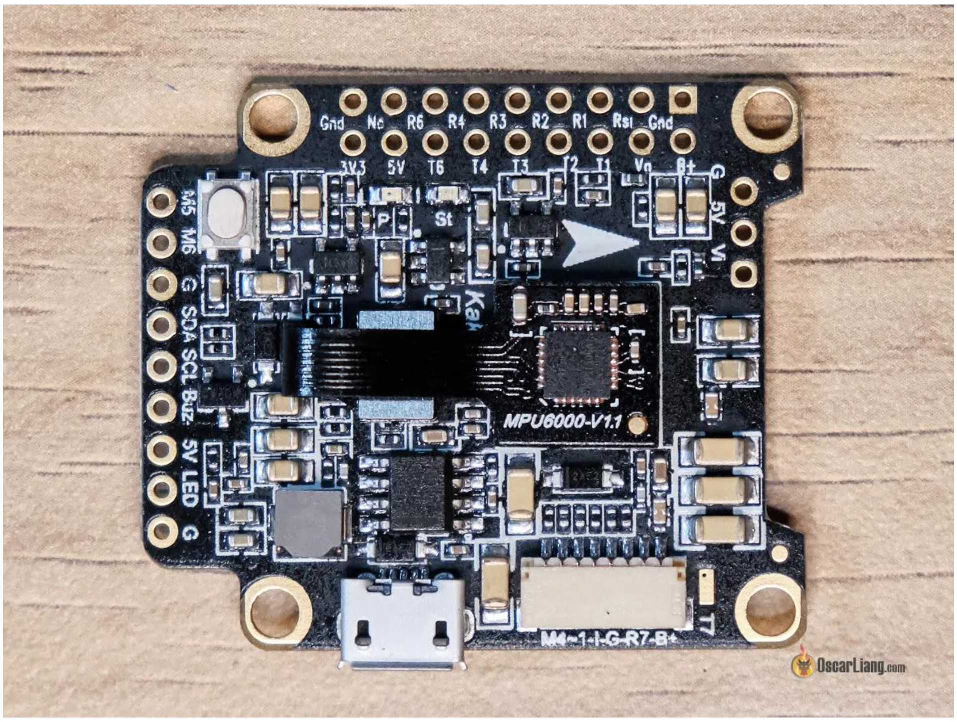


Fig. 2.11 Flight Control Card.

The Power Organizer: PDB (Power Distribution Board)

Not all drones need a PDB (Power Distribution Board), but for those that do, it's a handy tool for keeping things tidy. Think of it as a central organizer for the drone's electrical system.

This circuit board takes the power from the battery and distributes it efficiently to all the hungry components: the electronic speed controllers (ESCs) and the flight control board itself. In some PDBs, the power supply extends to other features like the camera, LED lights, and even the flight controller.

Overall, a PDB helps to streamline the wiring in your drone, making it easier to assemble, maintain, and keep things running smoothly.

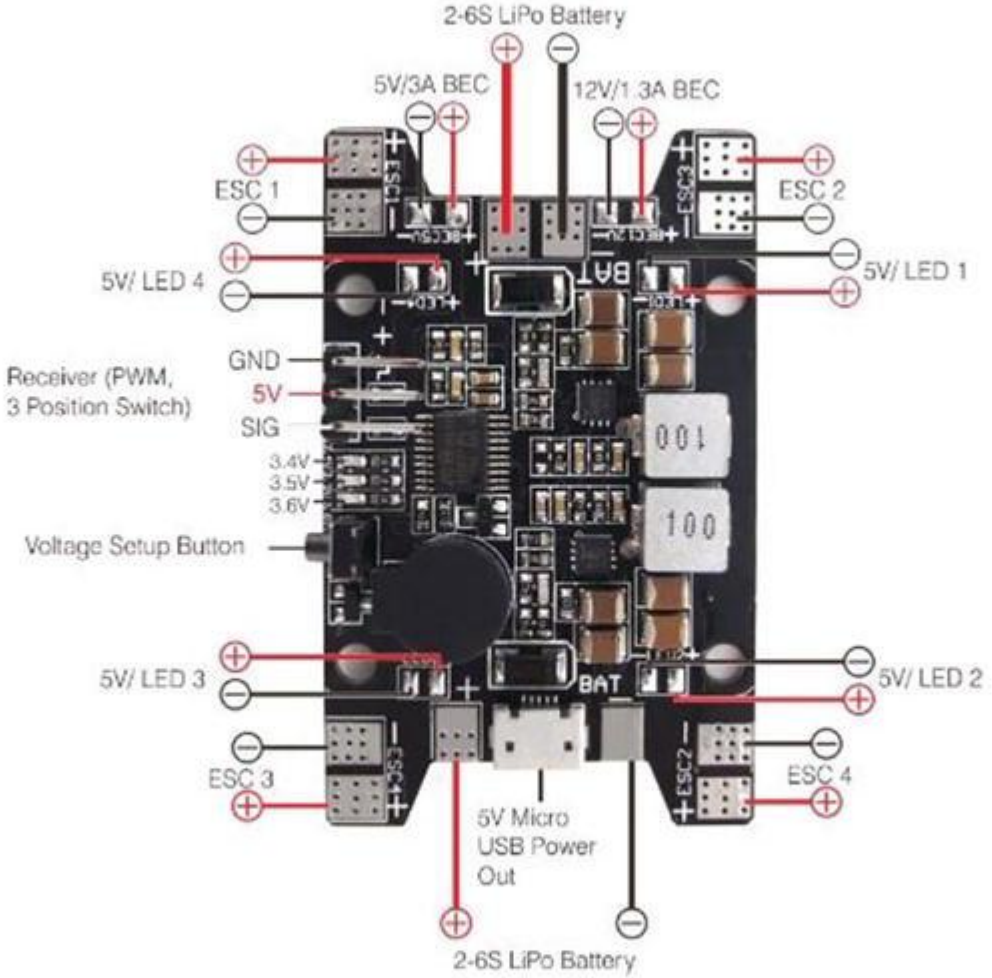


Fig. 2.12 Power Distribution Board.

Electronic Speed Controller (ESC)

The Electronic Speed Controller (ESC) is an essential component responsible for regulating the speed of the drone's brushless motors. Each motor requires its own dedicated ESC for precise control. In traditional setups, a separate ESC is connected to each individual motor branch. However, for a more compact and efficient solution, 4-in-1 ESC configurations are also available.

The ESC plays a crucial role in maintaining optimal drone performance. During troubleshooting of power-related issues, particularly those affecting specific motors, the ESC should be the initial focus for potential causes and solutions.

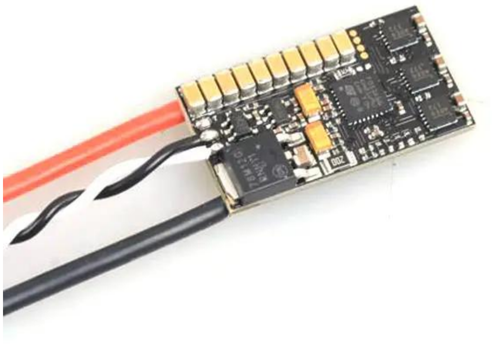


Fig. 2.13 Electronic Speed Controller (ESC).

The Drone Controller.

The drone controller serves as the pilot's primary interface, functioning as the command center for issuing flight instructions.

The number of channels on the controller dictates the complexity of commands it can transmit. A higher channel count allows for nuanced control and the integration of additional functionalities like camera operation.

A digital display on the controller enhances user experience by providing real-time data on flight parameters, battery life, and signal strength, similar to an instrument panel in a traditional aircraft.

The Drone Receiver.

The drone receiver acts as the sensory nervous system of the aircraft. It functions by receiving control signals transmitted by the controller via radio waves, acting as an intermediary between pilot input and flight control decisions.

These radio waves offer a reliable and near-instantaneous method of communication, ensuring precise and uninterrupted control of the drone.

Receivers typically come equipped with an integrated antenna for optimal signal reception.

The base functionality of a drone requires at least four channels for controlling movement along the vertical (altitude), horizontal (pitch and roll), and yaw (rotational) axes. However, many receivers offer additional, auxiliary channels that enable advanced features or programmable flight modes. Receivers with five or six channels are generally preferred for their increased versatility.

Fig. 2.14 Six-channel drone receiver..

Drones and Camera Integration

Modern drones have transcended their basic flight capabilities, transforming into powerful aerial imaging platforms. While not every drone boasts a camera system, many offer a plethora of in-flight options, including aerial photography, cinematic videography, and even an immersive first-person view (FPV) flight experience. Mirroring the diversity of drones themselves, camera systems come in a variety of configurations to cater to distinct applications. These systems typically include a gimbal (for image stabilization), video transmitter, antenna, and FPV goggles (for a pilot's-eye view).

The Core of FPV: Unveiling the FPV Camera

The FPV camera, strategically mounted at the front of the drone, transmits a real-time video feed directly to the pilot's display or goggles. These cameras come in two primary configurations: analog and HD. The image data first passes through the camera lens, where specialized sensors capture the scene and convert it into electrical signals. The video transmitter then relays these signals for viewing on the pilot's display. When selecting an FPV camera, critical factors to consider include sensor type (CCD or CMOS), sensor size, dynamic range, aspect ratio, field of view (FOV), latency (signal delay), and low-light performance.

CCD vs. CMOS: A Comparative Analysis of Sensor Technologies

Cameras primarily utilize two main sensor types: CCD and CMOS. CCD sensors capture all image data simultaneously, resulting in superior image fidelity with minimal distortion (often referred to as the "jelly effect"). Additionally, CCD sensors excel in dynamic range, effectively processing both brightly lit and low-light environments. However, CMOS sensors offer distinct advantages. They capture data line by line, enabling a more compact design. While this method can introduce a rolling shutter effect, CMOS sensors generally boast excellent color reproduction, lower power consumption, and a more attractive price point.

Sensor Size: A Critical Determinant of Image Quality

The size of the sensor plays a significant role in both low-light performance and dynamic range. Larger sensors enable a wider field of view and provide superior low-light capture capabilities due to their ability to accommodate larger lenses. Dynamic range ensures clear visibility in environments with varying light intensities by adjusting to accommodate both bright and dark areas. Camera aspect ratios typically fall into two categories: 16:9 and 4:3, with many modern cameras offering the flexibility of adjustable aspect ratios.

Field of View: Optimizing the Viewing Perspective

Field of view (FOV) and viewing angle are crucial considerations when selecting an FPV camera. A wider FOV provides a broader perspective, ideal for capturing expansive landscapes. However, this wider view can distort distant objects, creating a fisheye effect. Conversely, a narrower FOV offers a more focused, detailed view, making it suitable for navigating close-proximity obstacles. FOV can be manipulated by adjusting either the lens length or the sensor size.

Illuminating Low-Light Performance

The "lux" unit is a key metric for evaluating a camera's low-light performance. A higher lux rating signifies a camera's ability to capture clear images in low-light conditions. Sensor size also plays a vital role here. Larger sensors have a greater surface area, allowing them to capture more light, which can significantly improve low-light performance.

Additional Sensor

Modern cargo delivery drones leverage a sophisticated array of sensors to achieve safe, autonomous flight operations. These sensors play a critical role in enabling the drone to perceive its environment, navigate obstacles, and maintain stable flight dynamics. Here's a closer look at some key sensor technologies employed in cargo drone systems:

LiDAR (Light Detection and Ranging): LiDAR sensors function similarly to radar, but utilize pulsed laser light to generate highly detailed, three-dimensional (3D) point clouds of the environment. This 3D data is invaluable for obstacle avoidance, precise landing maneuvers, and terrain following, particularly in complex urban environments.

Global Navigation Satellite System (GNSS) and Inertial Measurement Unit (IMU): These complementary sensor systems provide essential data for the drone's flight control system. GNSS receivers, typically utilizing GPS technology, offer real-time positioning information. IMUs, comprised of accelerometers, gyroscopes, and magnetometers, continuously measure the drone's orientation, acceleration, and angular rates. By fusing data from both GNSS and IMUs, the flight control system can maintain precise navigation and stabilize the drone's flight path.

2.4 Existing examples of drone use in cargo delivery

2.4.1 Amazon Prime Air. [4]

Amazon Prime Air represents a pioneering effort in the realm of unmanned aerial vehicle (UAV) delivery. Launched in 2022, this service leverages drone technology to deliver customer packages autonomously.

Prime Air boasts the capability of delivering packages weighing up to five pounds (approximately 2.3 kilograms) within a remarkable timeframe of one hour. While currently operational in only two US cities, Amazon anticipates significant expansion by late 2024. The target destinations include the United Kingdom, Italy, and an additional undisclosed US city.

Seamless Ordering and Receipt: Customers can opt for drone delivery during checkout on Amazon.com, provided the chosen item qualifies. Look for the designation "FREE Drone delivery within 1 hour" to identify eligible products. Upon order confirmation, a Prime Air drone autonomously navigates to deliver the package directly to your doorstep. Prime Air's service area is presently limited to a select few regions. Current drone capabilities restrict deliveries to relatively lightweight packages.

Amazon Prime Air currently utilizes a custom-designed drone named the MK30. This innovative marvel of engineering boasts several distinctive features that empower its efficient and reliable delivery operations:

– Enhanced Range: The MK30 can traverse significantly farther distances compared to its predecessors extending its reach to customers residing in areas previously beyond the scope of drone delivery. News sources report the MK30 can operate within a range of up to 100 kilometers (62 miles).

– Mass and Cargo Capacity**:** While there's no official data on the MK30's weight, it's designed for package delivery. Packages delivered by drones typically weigh less than 5 kilograms (11 lbs). This suggests the MK30 itself is unlikely to exceed 25 kilograms (55 lbs).

– Reduced Noise Emissions: Amazon has prioritized noise reduction in the MK30's design, ensuring minimal disruption to neighborhoods during its operations.

– Compact Size: The MK30's sleek and compact design enables it to navigate with agility in urban environments, maneuvering around obstacles with enhanced precision.

– Safety Features: The MK30 is equipped with a suite of advanced safety features, including redundant flight systems, sense-and-avoid technology, and a robust safety enclosure..

– Vertical Takeoff and Landing (VTOL): The MK30's VTOL capabilities enable it to operate from compact spaces, eliminating the need for lengthy runways.

– Sense-and-Avoid Technology: The MK30 is equipped with sophisticated sense-and-avoid technology, enabling it to detect and safely navigate around obstacles, including static objects, moving vehicles, and other drones.

– Redundant Flight Systems: The MK30 incorporates redundant flight systems, ensuring continued operation even in the event of a single component failure.

– Robust Safety Enclosure: The MK30's safety enclosure protects both the drone and its surroundings during flight, minimizing the risk of damage or injury.

Fig. 2.15 Drone MK30.

Classification of the MK30 drone using my classification:

1) Control System: Remotely Controlled.

2) Type of aircraft: Convertoplane type.

3) Type of wing: Fixed-Wing hybrid VTOL.

4) Direction of takeoff/landing (method of lift): Takeoff: Vertical, landing: Horizontal.

5) Takeoff and landing type: Takeoff: Likely Airfield, Landing: Likely Airfield

6) Propulsion System: Unknown (possibly Electric or Piston)

7) Fuel System: Multi-Use (Reusable). Refueling Method: Unknown (possibly Ground Refueling)

8) Payload: Primary - Electro-Optical Camera (possibly with additional sensors)

The MK30 weight itself is around 25 kilograms (55 lbs), the upper limit for the Small category. MK30 can operate within a range of up to 100 kilometers (62 miles).This falls well within the range capabilities of the Small category (up to 100 kilometers).

Therefore, considering both payload capacity and operational range, the Small category seems like the most suitable fit for the MK30 drone.

Overall, the MK30 represents a culmination of cutting-edge drone technology, specifically tailored to meet the demands of Amazon Prime Air's delivery service. Its enhanced range, reduced noise emissions, compact size, safety features, cargo capacity, VTOL capabilities, sense-and-avoid technology, redundant flight systems, and robust safety enclosure position it as a key enabler in Amazon's quest to revolutionize package delivery.

2.4.2 Zipline. [5]

Zipline, a leading provider of autonomous drone delivery services, is revolutionizing the way medical products are delivered to remote and underserved communities. Utilizing their innovative Platform 1 drone, Zipline is bridging the gap in healthcare access, ensuring that life-saving medications and vaccines reach patients in need, regardless of their location.

Zipline’s Platform 1 drone is a marvel of engineering, designed specifically for medical product delivery. Platform 1 can efficiently transport a wide range of medical supplies, including blood, vaccines, and pharmaceuticals.

Streamlined Ordering and Fulfillment:

Medical personnel at remote healthcare facilities submit orders electronically, specifying the required medical supplies.

Dedicated fulfillment staff within the distribution center efficiently prepare and package the requested medical supplies for aerial delivery.

Rapid Launch and Autonomous Flight: Trained flight operators meticulously prepare the drones for each mission, ensuring airworthiness and payload security.

Utilizing a supercapacitor-powered electric catapult launcher, the drones achieve a swift takeoff, reaching speeds of up to 70 miles per hour within a fraction of a second.

Once airborne, the drones navigate autonomously to the designated delivery site, with a remote pilot at the distribution center providing real-time monitoring and oversight.

Precise Delivery and Efficient Return:

Upon reaching the pre-programmed delivery zone, the drone descends to a predetermined altitude and releases the medical supplies secured by a paper drogue parachute.

This innovative delivery system ensures pinpoint accuracy, consistently placing the payload within a 5-meter diameter landing zone.

Following a successful delivery, the drone autonomously returns to the distribution center, employing a tail hook to snag an arresting gear for a smooth and controlled landing, similar to aircraft carrier operations.

Resilient and Reliable System:

Zipline's drone delivery system boasts exceptional reliability, effectively delivering critical medical supplies within a 100-kilometer radius. This innovative solution remains operational even in challenging environments characterized by mountainous terrain or adverse weather conditions.

Platform 1’s autonomous capabilities are at the heart of its transformative impact. The drone seamlessly navigates the air, utilizing GPS, advanced sensors, and sophisticated software to avoid obstacles and ensure safe and secure deliveries. This autonomous operation eliminates the need for human pilots, reducing costs and increasing efficiency.

Zipline’s impact is evident in the lives it has saved. By providing timely delivery of critical medical products, Zipline has enabled healthcare providers in remote areas to effectively treat patients, preventing complications and fatalities. Moreover, Zipline’s technology is expanding access to healthcare for underserved communities, ensuring that even those in the most challenging locations can receive the medical care they need.

The company operates a network of distribution centers in Rwanda and Ghana, utilizing its innovative Platform 1 drone to deliver critical medical products to remote and underserved communities. Zipline’s mission is to save lives and improve healthcare access through the power of technology.

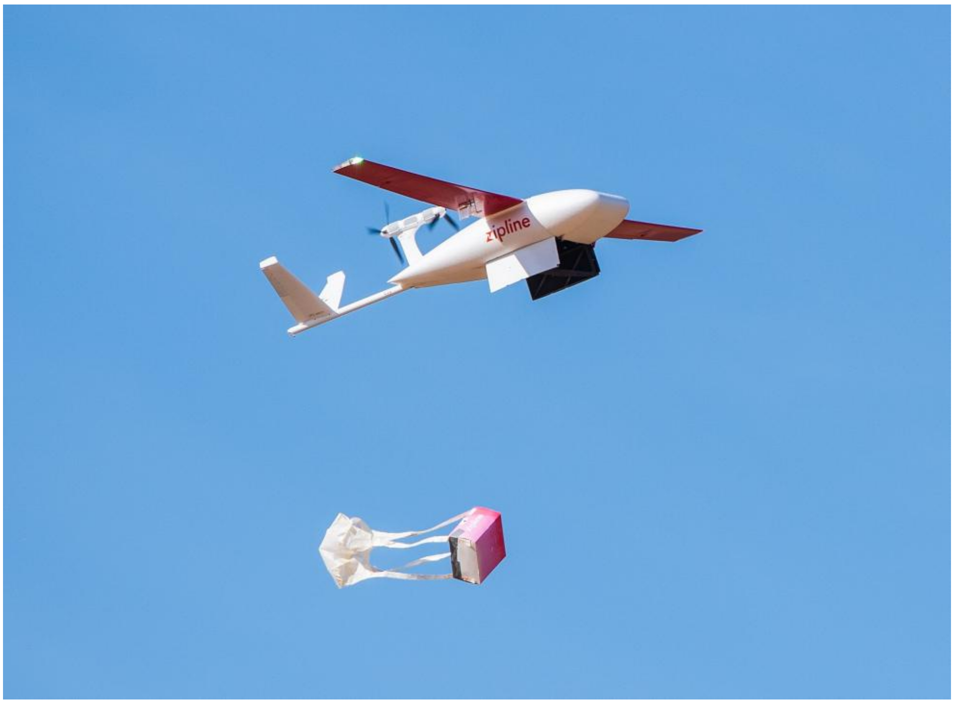


Fig. 2.16 Drone ‘Platform 1’ from Zipline.

Zipline Delivery Drone: Technical Specifications:

– Cruise Speed and Altitude: The Zipline drone boasts a cruising speed of 101 km/h (63 mph) while maintaining an operational altitude of 80-120 meters (260-390 ft) above ground level.

– Cargo Capacity: This unmanned aerial vehicle (UAV) is capable of carrying essential supplies weighing up to 4 pounds (1.8 kilograms).

– Range and Operational Radius: The drone's maximum range on a single charge is an impressive 300 kilometers (190 miles). However, for operational efficiency and safety purposes, deliveries are typically limited to an 80-kilometer (50-mile) radius.

– Rapid Battery Replacement: The drone utilizes a quick-swap battery system, facilitating swift turnaround times between deliveries.

– Durable Construction: The airframe features a robust inner frame constructed from carbon fiber, encased in a lightweight polystyrene shell for optimal performance.

– Aerodynamic Design: The drone possesses a wingspan of 11 feet (3.4 meters) for efficient flight characteristics.

– Assisted Launch System: The launch process employs an electric motor that propels the drone along a steel rail, achieving an acceleration of 0 to 67 mph (108 km/h) within 0.3 seconds.

– Redundant Propulsion System: For enhanced flight reliability, the drone is equipped with dual propellers. It is even capable of safe operation with a single propeller or motor in the event of a malfunction.

– Autonomous Navigation: One of the most remarkable features is the drone's ability to autonomously navigate and complete deliveries under normal weather conditions, eliminating the need for constant human oversight.

Classification of the Platform 1 drone using my classification:

1) Control System: Remotely Controlled with High Degree of Autonomy.

2) Type of aircraft: Airplane type.

3) Type of wing: Fixed-Wing.

4) Direction of takeoff/landing (method of lift): Horizontal for both takeoff and landing.

5) Takeoff and landing type: Takeoff: Electric Catapult Launch,
Landing: Airfield.

6) Propulsion System: Electric.

7) Fuel System: Multi-Use (Reusable). Refueling Method: Ground Refueling.

8) Payload: Uncertain (Cameras and Sensors likely)

The Platform 1 weight itself is around 25 kilograms (55 lbs), the lower limit for the Medium category. Platform 1 can operate within a range of up to 300 kilometers (186 miles).This falls well within the range capabilities of the Medium category (up to 500 kilometers).

2.4.3 DJI FlyCart 30. [6]

DJI, a world leader in consumer and professional drones headquartered in Shenzhen, China, has made a strategic leap into the burgeoning drone delivery market with the DJI FlyCart 30. This innovative offering marks a clear ambition for the company to carve out a significant share in this rapidly evolving field.

Founded in 2006, DJI has grown from a small startup to a global tech powerhouse. Their expertise in camera stabilization technology initially propelled them to the forefront of the drone industry. Since then, they've expanded their product line to include handheld cameras, gimbals, propulsion systems, and enterprise software. The DJI FlyCart 30 represents a natural extension of their core competencies – combining their mastery of flight technology with intelligent delivery solutions.

The FlyCart 30's impressive payload capacity, extended range, and versatile delivery methods like the winch system demonstrate DJI's commitment to staying at the forefront of drone technology. Beyond the technical prowess, DJI's entry into drone delivery suggests a broader strategic vision. The company might be aiming to leverage its strong brand reputation and extensive user base to establish a robust drone delivery ecosystem. This could involve not just the hardware itself, but also software solutions for fleet management, air traffic control integration, and data analysis – areas where DJI's experience in developing user-friendly platforms can prove advantageous.

It will be interesting to see how DJI navigates the complex regulatory landscape surrounding commercial drone deliveries. Their experience navigating airspace regulations for recreational drones could prove valuable. However, successfully navigating the stricter requirements for commercial deliveries will be a key hurdle to overcome. Regardless, DJI's foray into this space with the FlyCart 30 is a bold move that has the potential to redefine the future of drone deliveries.

Here's a breakdown of the DJI FlyCart 30 for cargo delivery:

– Payload: The FlyCart 30 boasts a maximum payload of 30 kilograms (66 lbs) in its dual-battery configuration with a delivery range of 16 kilometers (10 miles). It can handle even heavier payloads (up to 40 kg / 88 lbs) for shorter distances (8 km / 5 miles) with a single battery.

– Delivery Methods: The FlyCart 30 offers two delivery modes:

Cargo Box: A spacious cargo case allows for secure transportation of goods.

Winch System: For deliveries in areas without landing zones, a winch system with a 20-meter cable can lower payloads precisely.

– Flight Stability: The FlyCart 30 is designed for harsh environments and difficult operations.

– AR Projection: During winch deliveries, an AR projection system helps with accurate payload placement.

– Delivery Management: DJI offers a DJI DeliveryHub platform for efficient operation planning, monitoring, and data analysis.

The DJI FlyCart 30 is a powerful option for companies looking to enter the drone delivery space. Its impressive payload capacity, range, and winch system make it suitable for various delivery needs.

Fig. 2.17 Drone DJI FlyCart 30.

Classification of the DJI FlyCart 30 using my classification:

1) Control System: Remotely Piloted.

2) Type of aircraft: Helicopter type.

3) Type of wing: Propellers.

4) Direction of takeoff/landing (method of lift): Takeoff: Vertical, Landing: Vertical.

5) Takeoff and landing type:Takeoff: Multi-takeoff, Landing: Multi-landing.

6) Propulsion System: Electric.

7) Fuel System: Multi-Use (Reusable). Refueling Method: Ground Refueling.

8) Payload: Uncertain (Cameras and Sensors, Cargo Bay and Winch System)

The DJI FlyCart 30 falls into an interesting spot between categories in my table 1.

Weight: Based on its maximum takeoff weight of 95 kg (with dual batteries), the

FlyCart 30 falls into the Medium category (25 kg to 150 kg).

Range: However, with a maximum range of 16 km (with a full payload), its range falls within the Small category (up to 100 kilometers). So FlyCart 30 drone could fit into the Small-Medium category.

2.5 Comparison Table

Here's a comparison of the three drones that I described.

Table 2. Drone Comparison Table

Feature	Amazon MK30	Zipline Platform 1	DJI FlyCart 30
Control System	Remotely Controlled	Remotely Controlled with High Degree of Autonomy	Remotely Piloted
Type of Aircraft	Convertoplane	Airplane	Helicopter
Type of Wing	Fixed-Wing hybrid VTOL	Fixed-Wing	Propellers
Direction of takeoff/landing (method of lift) (Takeoff/Landing)	Vertical / Horizontal	Horizontal / Horizontal	Vertical / Vertical
Takeoff and landing type (Takeoff/Landing)	Airfield / Airfield	Electric Catapult Launch / Airfield	Multi-takeoff / Multi-landing
Propulsion System	Unknown (possibly Electric or Piston)	Electric	Electric
Fuel System	Multi-Use (Reusable)	Multi-Use (Reusable)	Multi-Use (Reusable)
Payload Capacity	Up to 5 kg (11 lbs)	Up to 1.8 kg (4 lbs)	Up to 40 kg (88 lbs)
Operational Range	Up to 100 km (62 miles)	Up to 300 km (186 miles)	Up to 16 km (10 miles) with full payload
Category	Small	Medium	Small-Medium

Chapter 2 conclusion

Through a comprehensive analysis of various delivery drones, including the Amazon MK30, Zipline Platform 1, and DJI FlyCart 30, I have concluded that helicopter type short-range delivery drones present the most compelling option for development at this time. Here's why:

Market Fit: Short-range delivery drones cater to a rapidly growing need – the swift and efficient delivery of goods within urban and suburban areas. This aligns perfectly with the increasing demand for e-commerce and on-demand services.

Technological Feasibility: Short-range drones benefit from existing advancements in battery technology, electric motors, and miniaturization. This allows for the development of commercially viable drones with a good balance of payload capacity, flight time, and operational cost.

Infrastructure Integration: Short-range drones can potentially integrate seamlessly with existing infrastructure. Landing pads on buildings or designated delivery zones can facilitate efficient and secure deliveries, minimizing disruption to the environment.

While long-range and high-payload drones offer exciting possibilities, the current technological and regulatory landscape suggests that short-range delivery drones have the greatest potential for near-term success. Their ability to address a growing market need, leverage existing technology, and navigate the regulatory environment positions them as a frontrunner in the drone delivery revolution.

Therefore, focusing development efforts on short-range delivery drones presents a strategic opportunity to capitalize on the burgeoning drone delivery market.

Furthermore, the decision to pursue a helicopter-type design is driven by several key advantages:

Vertical Takeoff and Landing (VTOL): This capability eliminates the need for lengthy runways, making it ideal for urban and suburban environments with limited space.

Maneuverability: Helicopter-type drones excel in precise maneuvering, allowing for controlled deliveries in tight spaces and around obstacles.

Stability: The inherent stability of helicopter designs can provide a smoother flight experience, potentially improving the handling of delicate cargo.

Price Consideration: While the exact cost will depend on specific features and payload capacity, short-range helicopter drones are expected to be more affordable than their long-range counterparts due to:

– Simpler design compared to fixed-wing drones.

– Lower battery requirements due to shorter flight distances.

– Less reliance on complex infrastructure for operation.

In conclusion, short-range helicopter drones offer a compelling path for capitalizing on the burgeoning drone delivery market. Their market fit, technological feasibility, infrastructure integration, price advantage, and maneuverability make them a strong contender for near-term success in revolutionizing the way we receive goods. My goal in chapter 3 will be to build a short-range helicopter drone for cargo delivery.

CHAPTER 3

MATHEMATICAL MODEL. STABILIZATION AND TRAJECTORY CONTROL OF A QUADCOPTER.

3.1 Mathematical Model

Before describing the mathematical model, it is necessary to introduce the relative coordinate system used to determine the position of the object. For a quadcopter, two relative reference systems can be used, which are shown in Fig. 1. The first is stationary (inertial), and the second is moving (non-inertial). The inertial coordinate system is a system in which Newton's first law applies. The moving coordinate system is associated with the center of mass of the quadcopter. The O_{NED} system is used for the inertial coordinate system, where N is north, E is east, and D is down (the vector is directed towards the center of the Earth). For the moving system, the O_{ABC} system is used.

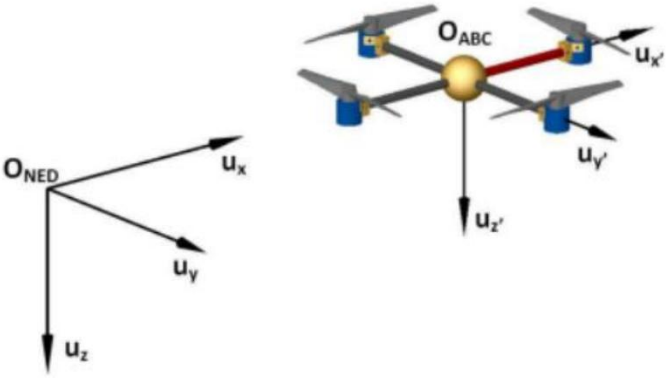


Fig. 3.1 Stationary and Moving Relative Coordinate Systems

To describe the orientation of a rigid body, we can use Euler angles. These angles allow us to transform the coordinates of a point in one reference frame to the coordinates of the same point in another reference frame.

Any position of the body can be represented by three successive rotations, which are described by the following rotation matrices:

$$R_x(\phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix} \tag{3.1}$$

$$R_y(\theta) = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \tag{3.2}$$

$$R_z(\psi) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3.3}$$

The position coordinates in the moving and fixed reference frames are related by a general rotation matrix, which is the product of three individual matrices:

$$R_{zyx}\,(\phi,\theta,\psi) = \ R_x(\phi) * R_y(\theta) * \ R_z(\psi) =$$

$$= \begin{bmatrix} \cos\theta\cos\psi & \sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi & \cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi \\ \cos\theta\sin\psi & \sin\phi\sin\theta\sin\psi - \cos\phi\cos\psi & \cos\phi\sin\theta\sin\psi + \sin\phi\cos\psi \\ -\sin\theta & \sin\phi\cos\theta & \cos\phi\cos\theta \end{bmatrix} \tag{3.4}$$

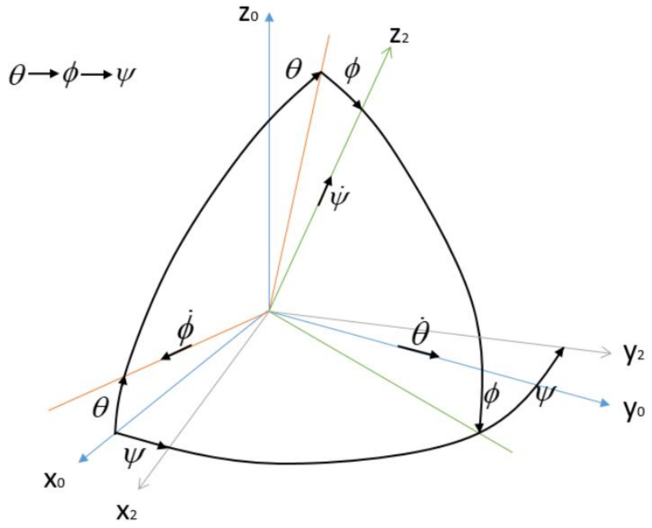


Fig. 3.2 Euler angles

The mathematical model of the quadrotor dynamics is derived using Newton's and Euler's laws to describe the motion of a rigid body in space.

First, we define two vectors containing the linear and angular position of the quadrotor in the inertial reference frame, and the linear and angular velocity of the quadrotor in the non-inertial reference frame, respectively:

$$[x\ y\ z\ \phi\ \theta\ \psi]^{\,T}$$

$$[u\ v\ w\ p\ q\ r]^T$$

Two reference frames are related by the following relationships:

$$\begin{aligned} v &= \ R * v_B \\ \omega &= \ T * \omega_B \end{aligned} \tag{3.5}$$

$$v = \ [\dot{x}\ \dot{y}\ \dot{z}]^T, \omega = \ \left[\dot{\phi}\ \dot{\theta}\ \dot{\psi}\right]^T, v_B = \ [u\ v\ w]^T, \omega_B = \ [p\ q\ r]^T$$

$$T = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \frac{\sin\,\phi}{\cos\,\theta} & \frac{\cos\,\phi}{\cos\,\theta} \end{bmatrix} \tag{3.6}$$

Therefore, the kinematic model of the quadcopter can be written as follows:

$$\begin{cases} \dot{x} = w[\sin\phi\sin\psi + \cos\phi\cos\psi\sin\theta] - v\,[\cos\phi\sin\psi - \cos\psi\sin\phi\sin\theta\,] + u\,[\cos\psi\cos\theta] \\ \dot{y} = v[\cos\phi\cos\psi + \sin\phi\sin\psi\sin\theta] - v\,[\cos\psi\sin\phi - \cos\phi\sin\psi\sin\theta\,] + u\,[\cos\theta\cos\psi] \\ \dot{z} = w\,[\cos\phi\cos\theta] - u\,[\sin\theta] + v\,[\cos\theta\sin\phi] \\ \dot{\phi} = p + r[\cos\phi\tan\theta] + q[\sin\phi\tan\theta] \\ \dot{\theta} = q[\cos\phi] - r\,[\sin\phi] \\ \dot{\psi} = r\frac{\cos\,\phi}{\cos\,\theta} + q\frac{\sin\,\phi}{\cos\,\theta} \end{cases} \tag{3.7}$$

Newton's laws define the following relationship matrix for the total force acting on the quadcopter:

$$m(\omega_B * \, v_B + \, \dot{v_B}) = \, f_B \tag{3.8}$$

Where m – mass of quadcopter, $f_B = \, [f_x \; f_y \; f_z]^T$ - General force

Euler's equations define the total moment applied to the quadcopter as follows:

$$I * \dot{\omega}_B * \omega_B * (I * \omega_B) = \, m_B$$

Where

$$m_B = \, [m_x \; m_y \; m_z]\,^T, I = \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix} \tag{3.9}$$

The origin and axes of the body reference frame coincide with the center of mass of the body and the principal axes.

From this we obtain the dynamic model of the quadcopter in the body reference frame:

$$\begin{cases} f_x = m(\dot{u} + qw - rv) \\ f_y = m(\dot{v} - pw + ru) \\ f_z = m(\dot{w} + pv - qu) \\ m_x = \, \dot{p}I_x - qrI_y + qrI_z \\ m_y = \, \dot{q}I_y - prI_x + prI_z \\ m_z = \, \dot{r}I_z - pqI_x + pqI_z \end{cases} \tag{3.10}$$

There are a number of forces and moments that affect the dynamics of a quadcopter. These include the following: the total thrust f_t, which occurs when the rotors rotate, the wind forces f_ω , which act on the quadcopter, the control moments τ , which are obtained due to the difference in the speed of the rotors, and the moments τ_ω , formed by the wind, which act on the quadcopter. Taking into account the specified forces and moments, the dynamic model of the quadcopter will have the following form:

$$\begin{cases} -mg[\sin\theta] + f_{\omega x} = m(\dot{u} + qw - rv) \\ mg[\cos\theta\sin\phi] + f_{\omega y} = m(\dot{v} - pw + ru) \\ mg[\cos\theta\sin\phi] + f_{\omega z} - f_t = m(\dot{w} - pv + qu) \\ \tau_x + \tau_{wx} = \dot{p}I_x - qrI_y + qrI_z \\ \tau_y + \tau_{wy} = \dot{q}I_y - prI_x + prI_z \\ \tau_z + \tau_{wz} = \dot{r}I_z - pqI_x + pqI_y \end{cases} \tag{3.11}$$

Consider the control values of the system for controlling the behavior of the quadcopter. There are four degrees of freedom in total: thrust and three angular motions. The values of the input forces and moments are proportional to the squares of the speed of each of the rotors, they have the following form:

$$\begin{cases} f_t = b(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2) \\ \tau_x = bl(\Omega_3^2 - \Omega_1^2) \\ \tau_y = bl(\Omega_4^2 - \Omega_2^2) \\ \tau_z = d(\Omega_2^2 + \Omega_4^2 - \Omega_1^2 - \Omega_3^2) \end{cases} \tag{3.12}$$

Where l is the distance between any rotor and the center of the quadcopter, b is the thrust coefficient, d is the resistance coefficient, **Ω** is the speed of the corresponding rotor.

According to Newton's law, the dynamic model can be written in the following form:

$$\begin{cases} \ddot{x} = -\frac{f_t}{m}[\sin\phi\sin\psi + \cos\phi\cos\psi\sin\theta] \\ \ddot{y} = -\frac{f_t}{m}[\cos\phi\sin\psi\sin\theta - \cos\psi\sin\phi] \\ \ddot{z} = g - \frac{f_t}{m}[\cos\phi\cos\theta] \end{cases} \tag{3.13}$$

Let's make the following simplification: $[\dot{\phi}\ \dot{\theta}\ \dot{\psi}] = [p\ q\ r]$, which is valid for small angular movements.

From this, the dynamic model of the quadcopter in the inertial (stationary) frame of reference will look like this:

$$\begin{cases} \ddot{x} = -\frac{f_t}{m}\,[\sin\phi\sin\psi + \cos\phi\cos\psi\sin\theta] \\ \ddot{y} = -\frac{f_t}{m}[\cos\phi\sin\psi\sin\theta - \cos\psi\sin\phi] \\ \ddot{z} = g - \frac{f_t}{m}[\cos\phi\cos\theta] \\ \ddot{\phi} = \frac{I_Y - I_Z}{I_X}\dot{\theta}\dot{\psi} + \frac{\tau_X}{I_X} \\ \ddot{\theta} = \frac{I_Z - I_X}{I_Y}\dot{\phi}\dot{\psi} + \frac{\tau_Y}{I_Y} \\ \ddot{\psi} = \frac{I_X - I_Y}{I_Z}\dot{\phi}\dot{\theta} + \frac{\tau_Z}{I_Z} \end{cases} \tag{3.14}$$

Let's define the control vector u

$$u = [f_t\ \tau_x\ \tau_y\ \tau_z]$$

Control of the position of the center of mass in space can be implemented using an open circuit, as shown in Fig. 3. The feedback element in this case is the operator

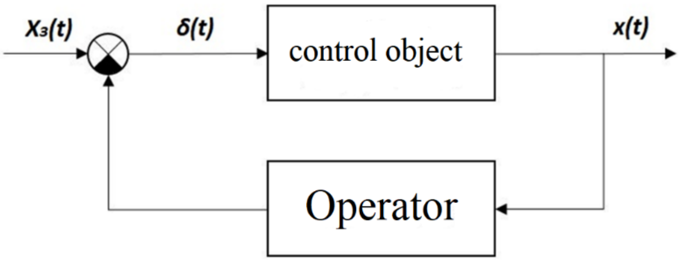


Fig. 3.3 Structural scheme of controlling the position of the center of mass in space.

To stabilize the angular position, you can use the scheme shown in Fig. 4. The sensors are the accelerometer and the gyroscope. W33(p) is the transfer function of the control system.

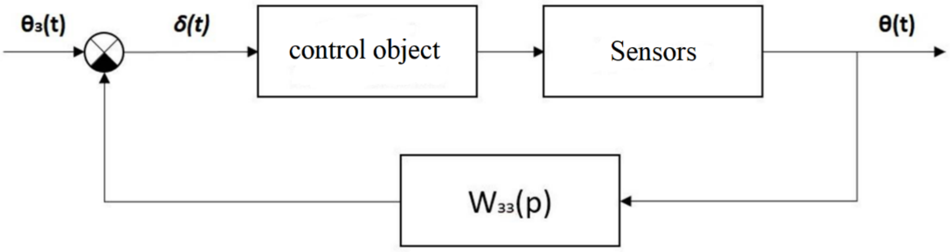


Fig. 3.4 Structural scheme for stabilizing the angular position.

3.2 Stabilization of quadcopter

PID controllers are a popular choice for stabilizing quadcopter attitude due to their simple structure and ease of implementation, making them both understandable and readily integrated into the flight control system.

$$e(t) = x_d(t) - x(t)$$

$$u(t) = K_p e(t) + K_I \int_0^t e(\tau)\, d\tau + K_D \frac{de(t)}{dt}$$

(3.15)

in which $u(t)$ is the control input, $e(t)$ is the difference between the desired state $x_d(t)$ and the present state $x(t)$, and K_p, K_I ,and K_D,are the parameters for the proportional, integral and derivative elements of the PID controller.

In a quadcopter, there are six states, positions **ξ** and angles **η**, but only four control inputs, the angular velocities of the four rotors ω_i .The interactions between the states and the total thrust **T** and the torques **τ** created by the rotors. The total thrust **T** affects the acceleration in the direction of the z-axis and holds the quadcopter in the air. Torque $\tau_\phi$has an affect on the acceleration of angle φ, torque τ_θ affects the acceleration of angle θ, and torque τ_ψ contributes in the acceleration of angle ψ.

The PD controller for the quadcopter is

$$T = (g + K_{z,D}(\dot{z}_d - \dot{z}) + K_{z,P}(z_d - z))\, \frac{m}{C_\phi C_\theta},$$

$$\tau_\phi = (K_{\phi,D}(\dot{\phi}_d - \dot{\phi}) + K_{\phi,P}(\phi_d - \phi))\, I_{xx} \, ,$$

(3.16)

$$\tau_\theta = (K_{\theta,D}(\dot{\theta}_d - \dot{\theta}) + K_{\theta,P}(\theta_d - \theta))\, I_{yy} \, ,$$

$$\tau_\psi = (K_{\psi,D}(\dot{\psi}_d - \dot{\psi}) + K_{\psi,P}(\psi_d - \psi))\, I_{zz}$$

in which also the gravity g, and mass m and moments of inertia I of the quadcopter are considered.

The correct angular velocities of rotors ω_i can be calculated from Equations

$$\omega_1^2 = \frac{T}{4k} - \frac{\tau_\theta}{2kl} - \frac{\tau_\psi}{4b}$$

$$\omega_2^2 = \frac{T}{4k} - \frac{\tau_\phi}{2kl} + \frac{\tau_\psi}{4b}$$

(3.17)

$$\omega_3^2 = \frac{T}{4k} + \frac{\tau_\theta}{2kl} - \frac{\tau_\psi}{4b}$$

$$\omega_4^2 = \frac{T}{4k} + \frac{\tau_\phi}{2kl} + \frac{\tau_\psi}{4b}$$

3.3 Trajectory control

The purpose of trajectory control is to move the quadcopter from the original location to the desired location by controlling the rotor velocities of the quadcopter. Finding an optimal trajectory for a quadcopter is a difficult task because of complex dynamics. However, a simple control method is able to control the quadcopter adequately.

The basis of the development of a control method is the study of the interactions and dependencies between states, state derivatives and control inputs.

The given control inputs ω_i define the total thrust T and the torques τ_i , τ_θ and τ_ψ. The torques affect the angular accelerations depending on the current angles and angular velocities. The angles η can be integrated from the angular velocities $\dot{\eta}$, which are integrated from the angular accelerations $\ddot{\eta}$. The linear accelerations $\ddot{\xi}$ depend on the total thrust T, the angles η and the linear velocities $\dot{\xi}$. The linear position ξ is integrated from the linear accelerations $\ddot{\xi}$ through the linear velocities $\dot{\xi}$

To find proper control inputs ω_i for given states ξ this line has to be done in reverse

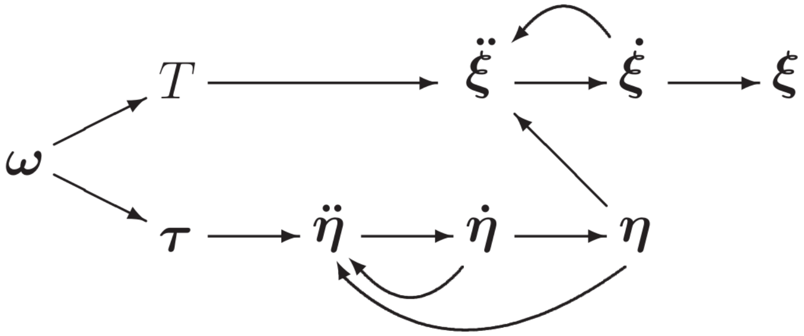


Fig. 3.5 Interactions between states, state derivatives, and control inputs

One method is to generate linear accelerations which accomplish the wanted trajectory according to positions x, y and z for each time t.

$$T_B = \begin{bmatrix} 0 \\ 0 \\ T \end{bmatrix} = R^T \left(m \left(\ddot{\xi} + \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} \right) + \begin{bmatrix} A_x & 0 & 0 \\ 0 & A_y & 0 \\ 0 & 0 & A_z \end{bmatrix} \dot{\xi} \right) \qquad (3.18)$$

In which $\ddot{\xi}$, $\dot{\xi}$, and ψ are desired trajectory values as well as angles φ and θ and total thrust T are unknown values to be solved. From this equation, the required angles φ and θ and the total thrust T for each time t can be calculated.

$$\phi = arcsin \left(\frac{d_x S_\psi - d_y C_\psi}{d_x^2 + d_y^2 + (d_z + g)^2} \right),$$

$$\theta = arctan \left(\frac{d_x C_\psi - d_y S_\psi}{d_z + g} \right),$$

(3.19)

$$T = m(d_x\,(S_\theta C_\psi C_\phi + S_\psi S_\phi) + d_y\,(S_\theta S_\psi C_\phi - C_\psi S_\phi) + (d_z + g)\,C_\theta C_\phi)$$

In which

$$d_x = \ddot{x} + A_x \dot{x}/m,$$

$$d_y = \ddot{y} + A_y \dot{y}/m,$$

(3.20)

$$d_z = \ddot{z} + A_z \dot{z}/m,$$

When the values of the angles φ and θ are known, the angular velocities and accelerations can be calculated from them with simple derivation.

3.4 Integrated PD controller

This method to take into account the possible deviations in the angles, is to integrate a PD controller into the heuristic method.The required values dx, dy, and dz in Equation 5 are given by the PD controller considering the deviations between the current and desired values (subscript d) of the positions ξ, velocities $\dot{\xi}$, and accelerations $\ddot{\xi}$.

$$d_x = K_{x,P}(x_d - x) + K_{x,D}(\dot{x}_d - \dot{x}) + K_{x,DD}(\ddot{x}_d - \ddot{x}),$$

$$d_y = K_{y,P}(y_y - y) + K_{y,D}(\dot{y}_d - \dot{y}) + K_{y,DD}(\ddot{y}_d - \ddot{y}),$$

(3.21)

$$d_z = K_{z,P}(z_d - z) + K_{z,D}(\dot{z}_d - \dot{z}) + K_{z,DD}(\ddot{z}_d - \ddot{z}),$$

Then, the commanded angles φc and θc and thrust T are given by Equation 5.The torques τ are controlled by the PD controller in Equation 4, same as in Equation 8. The control inputs can be solved with the calculated thrust and torques by using Equation 3.

$$\tau_\phi = (K_{\phi,P}(\phi_c - \phi) + K_{\phi,D}(\dot{\phi}_c - \dot{\phi}))\, I_{xx}\ ,$$

$$\tau_\theta = \left(K_{\theta,P}(\theta_c - \theta) + K_{\theta,D}(\dot{\theta}_c - \dot{\theta})\right) I_{yy} \ ,$$

(3.22)

$$\tau_\psi = \left(K_{\psi,P}(\psi_c - \psi) + K_{\psi,D}(\dot{\psi}_c - \dot{\psi})\right) I_{zz} \ ,$$

Chapter 3 conclusion

This chapter established a comprehensive mathematical model for a quadcopter, leveraging Newton's and Euler's laws to describe its rigid body dynamics and the influences of external forces and moments. This model lays the groundwork for further analysis and control design of quadcopter systems.

We investigated control methodologies for the quadcopter, including PID controllers for stabilizing its attitude and a heuristic approach for trajectory control. The chapter culminated by proposing an integrated control strategy that combines these techniques. This strategy incorporates a PD controller within the heuristic method to account for potential deviations in the quadcopter's angular position.

This mathematical modeling framework serves as a foundation for future work exploring more sophisticated control algorithms to optimize the quadcopter's performance and enhance its trajectory tracking capabilities.

CHAPTER 4

DRONE ASSEMBLY. CONTROLLER MODES AND CONTROL LAWS.

4.1 Drone structural scheme, components and tools

Before we start the assembly and development process, we need to finalize the drone's structure. The proposed structure (Fig. 4.1) is a basic drone design with remote control and programmable delivery capabilities. This is the structure we will be using.

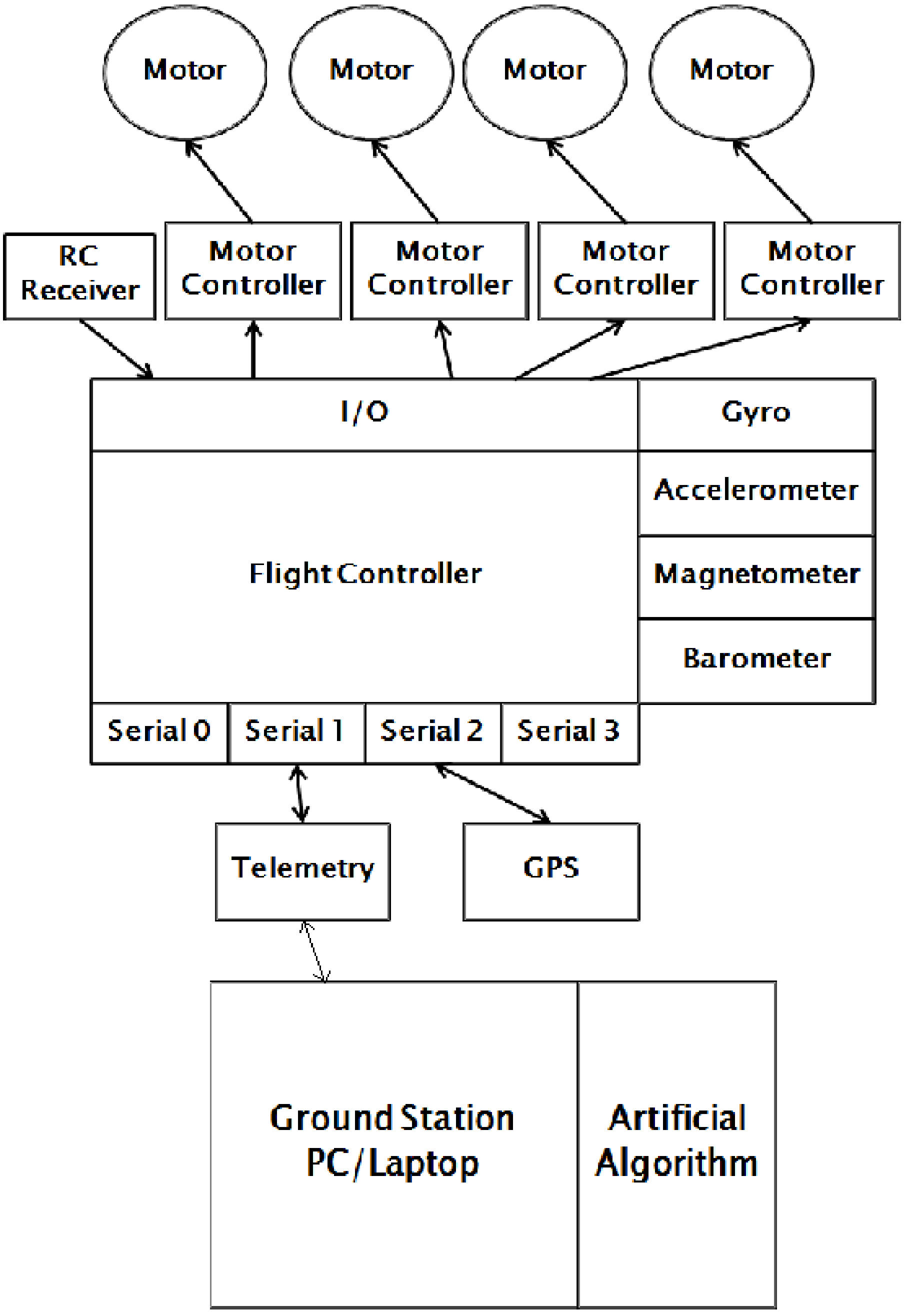


Fig. 4.1 Drone structural scheme

4.1.1 Tools and Materials for Building a Cargo Delivery Quadcopter.

Equipment and Tools:

– Soldering Iron/Station: A high-quality soldering iron or station is crucial for establishing reliable electrical connections between electronic components. Soldering stations offer superior temperature control for optimal results. Consider a station with an integrated hot air gun for efficient heat shrink application.

– Solder: Select a low-melting-point solder specifically formulated for electronic applications. A melting temperature below 185°C is recommended. POS 61 solder is a popular choice. Choose the appropriate diameter based on the application: 0.1mm for delicate connections and 0.4-0.8mm for larger components.

– Soldering Paste: Enhance your soldering experience with soldering paste. This specialized flux aids in removing metal oxides and preventing oxidation, ensuring smooth and reliable solder joints.

– Multimeter: A vital tool for any electronics workbench, a multimeter allows you to measure voltage, current, identify short circuits, and verify the integrity of your soldered connections.

– Hex Key Set: A hex key set, encompassing sizes from 1.3mm to 6mm, is essential for tightening and loosening motor screws and frame fasteners.

Screwdrivers:

– Screwdriver Set: Equip yourself with a comprehensive set of small screwdrivers for various assembly tasks. An interchangeable head screwdriver with hex key compatibility offers ultimate versatility.

– Wire Cutters, Strippers, and Pliers: Prior to soldering, wires require proper preparation. Utilize wire cutters to achieve the desired length, followed by wire strippers to remove insulation cleanly for optimal connections. Pliers provide a helping hand for holding wires during the soldering process.

– Electrical Tape: Electrical tape offers a convenient solution for temporarily covering exposed wires on the Electronic Speed Controller (ESC), particularly when heat shrink tubing is unavailable.

– Heat Shrink Tubing: For a more permanent and reliable solution for insulating exposed wires and components, use heat shrink tubing. Slide it over the desired area after soldering, then shrink it using a hot air gun to create a secure and professional finish. While electrical tape can be used as a substitute in emergencies, it's not recommended for long-term use due to potential wear and tear.

– Glue Gun: A glue gun provides a strong adhesive bond for securing wires to the board and for other mounting applications.

Connector Selection:

– Connector Set: Select the appropriate connector size based on your drone's specific requirements. XT60 connectors are commonly used for 3-inch and larger drones, while XT30 connectors are suitable for smaller models. JST connectors cater to low-power devices, and XT90 connectors are ideal for high-power applications.

Threadlocker:

– Threadlocker: Over time, vibrations can cause propeller screws and locknuts to loosen. Apply threadlocker to these fasteners to ensure they remain securely in place.

4.1.2 Components

To assemble a cargo delivery drone we will need the following components:

– 295mm Carbon Fiber Frame for 7" Propellers: This lightweight and durable carbon fiber frame provides a sturdy foundation for drone and is specifically designed to accommodate 7-inch propellers.

– 4x 2806 1300kv Motors: These powerful and efficient motors deliver the necessary thrust to lift the drone and its payload. The 1300kv rating indicates their revolutions per minute per volt, ensuring they are well-suited for this application.

– 4-in-1 60A ESC with XT-60 Connector and Capacitor: This integrated ESC unit simplifies wiring and provides precise control over your motors. The 60A rating indicates its continuous current capacity, ensuring it can handle the power requirements of motors. The XT-60 connector is a common standard for power connections in drones. The included capacitor helps smooth out power delivery.

– F7 Flight Controller: This advanced flight controller provides the brains for drone, handling essential tasks like stabilization, navigation, and flight control. The F7 chip ensures fast processing and responsiveness.

– 2.4GHz Receiver: This receiver allows you to control drone using a compatible transmitter. The 2.4GHz frequency band is widely used for drone communication due to its reliability and range.

– Digital System with Camera: This digital video transmission system provides real-time video feedback from the drone's camera, allowing you to monitor its flight and surroundings. The digital format ensures high-quality and low-latency video transmission.

– 7-inch Propellers: These propellers are specifically designed to work with the motors and frame to generate efficient lift and thrust for drone.

– 2600mAh 6S LiPo Battery: This high-capacity 6S LiPo battery provides the necessary power to drone's motors and electronics. The 2600mAh capacity ensures sufficient flight time for cargo delivery missions.

– 2.4GHz Radio Controller: This radio controller allows you to remotely control drone's flight, including throttle, yaw, pitch, and roll. The 2.4GHz frequency band matches the receiver for reliable communication.

– Full Metal Aluminum Alloy Claw

– Global Navigation Satellite System (GNSS) Module: A GPS or combined GPS & GLONASS module provides the drone with its location and allows for waypoint navigation and geo-fencing.

– Differential Global Positioning System (DGPS) (Optional): Improves the accuracy of the GPS signal for more precise navigation, especially important for deliveries in tight spaces.

– Barometer: Measures altitude and air pressure, crucial for maintaining flight stability and altitude control.

– Differential Pressure Sensor (Airspeed Sensor): Measures the drone's airspeed relative to the air mass, important for maintaining stable flight and for certain autonomous flight modes.

– Inertial Measurement Unit (IMU): Combines an accelerometer, gyroscope, and magnetometer to provide data on the drone's orientation, acceleration, and rotation, all critical for flight control and stabilization.

4.2 Approximation Estimates for my drone's characteristics:

Estimated Weight: 650 grams to 800 grams

Maximum Range:

Flight Time Estimate: Based on a conservative 6 minutes per 1000mAh of battery capacity (under hovering conditions), 2600mAh 6S LiPo battery offers a potential flight time of 15.6 minutes (2600mAh * 0.001Ah/mAh * 6 minutes/mAh).

Conversion to Distance: Assuming an average speed of 40 kilometers per hour (kmph), this translates to a maximum range of roughly 10.4 kilometers (15.6 minutes * 40 kmph / 60 minutes/hour).

Maximum Weight Capacity: Typically, 7-inch drones can handle payloads between 1.5kg and 2.5kg. I assume that my drone will carry at least 2 kg of weight.

4.3 Assembly

Drone Assembly Steps:

1. Partial Frame Assembly
2. Mount Motors
3. Install Camera and Video Transmitter
4. Solder Power Wires and Connectors
5. Mount 4-in-1 ESC
6. Mount Flight Controller
7. Install RC Receiver and Sensors:
   – Global Navigation Satellite System (GNSS) Module (GPS or combined GPS & GLONASS)
   – Differential Global Positioning System (DGPS) (Optional)
   – Barometer
   – Differential Pressure Sensor (Airspeed Sensor)
   – Inertial Measurement Unit (IMU)
8. Solder Receiver to Flight Controller
9. Route and Secure Wires
10. Complete Frame Assembly
11. Mounting a PWM servo gripper

First Step - Partial Frame Assembly

Start by assembling the bottom plate and arms. Ensure the arms are oriented correctly with the small hole on the top side, where the motors will be mounted.

Attach the struts but leave the top cover off for later installation of electronic components. Also, don't mount the antenna mount yet.

Fig. 4.2 Partial Frame Assembly

Second Step - Motor Installation

Mount the motors onto the top ends of each arm, ensuring the power and signal wires are facing the center of the drone.

Secure the wires with electrical tape for protection.

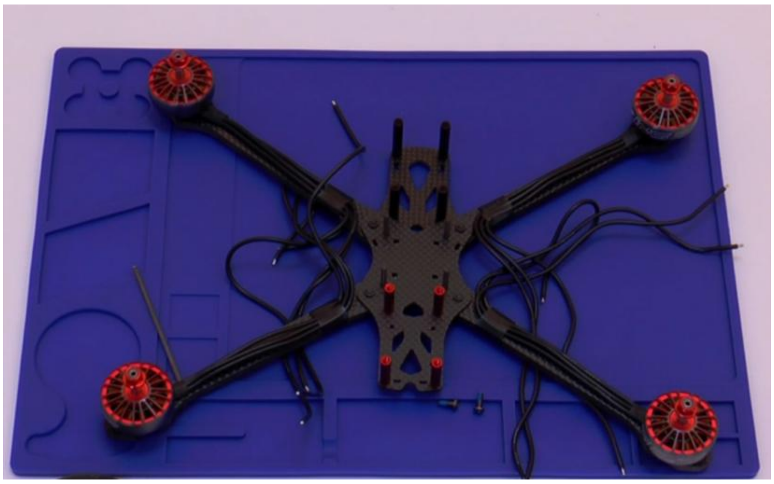


Fig. 4.3 Motor Installation

Third Step - Camera and Video Transmitter Installation

The camera is already connected to the video transmitter. Solder the connecting wires to the video transmitter, which will later be attached to the flight controller. Refer to the video transmitter's manual for wire and pad locations.

Thread the video transmitter's antenna through the antenna mount and secure it to the transmitter.

Mount the camera and video transmitter in their designated spots. The camera is mounted with two short M2 screws in the front, using M2 plastic washers if necessary. The video transmitter is mounted with long M2 screws and M2 nuts in the rear.

Route the camera's video cable along the center of the drone, where other components will be mounted above it.

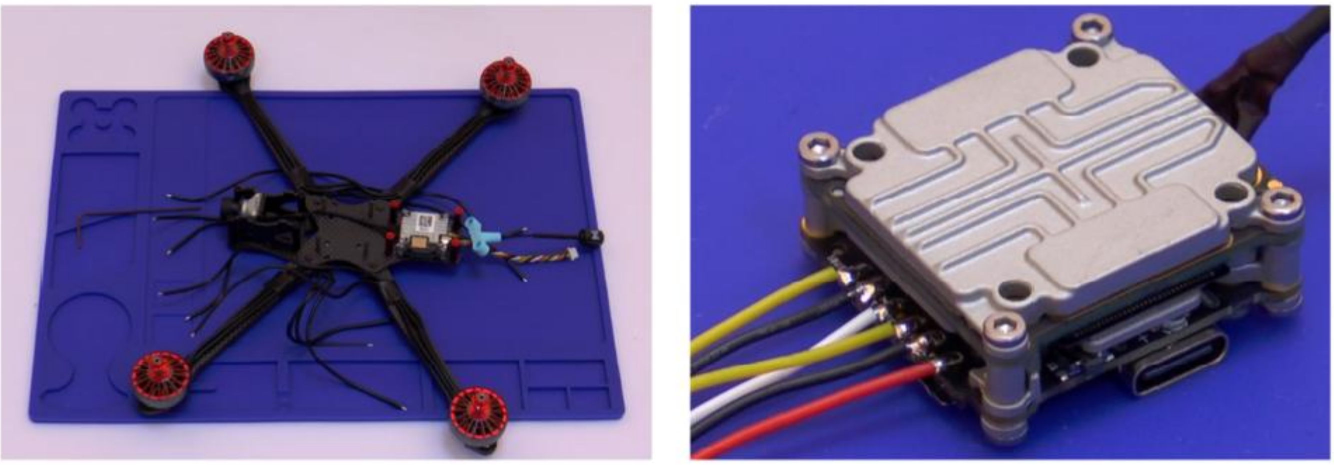


Fig. 4.4 Camera and Video Transmitter Installation

Fourth Step - Power Wire and Connector Soldering

Solder the power cables to the connector, ensuring red is positive and black is negative.

To reduce electrical interference, use a 10µF 35V electrolytic capacitor. Solder it near the connector due to limited space.

Solder the power wires to the ESC (Electronic Speed Controller), maintaining polarity. Insulate the solder joints with sealant, tape, or heat shrink tubing. Avoid overheating the PCB.

Fig. 4.5 Solder the power wires to the ESC

Fifth Step - 4-in-1 ESC Installation

Mount the ESCs onto the bolts prepared during frame assembly. Use rubber dampers between the PCB and metal bolts for vibration isolation and electrical insulation.

Solder the motor leads to the ESC. Tin the pads on the ESC and the motor wires.

Cut the wires to an appropriate length, avoiding slack or tension.

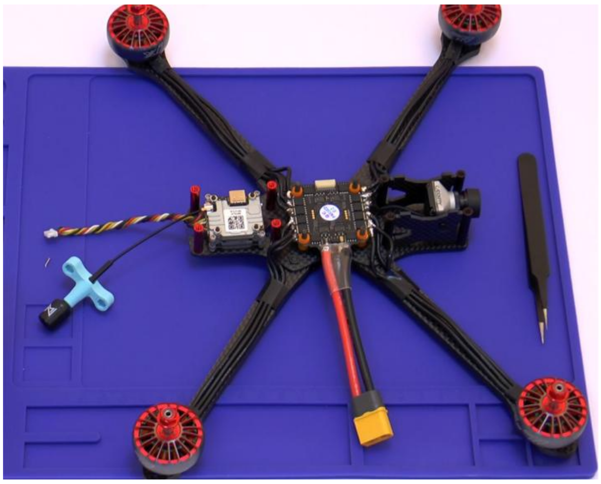


Fig. 4.6 4-in-1 ESC Installation

Sixth Step - Flight Controller Installation

Mount the flight controller above the ESCs, using rubber dampers. Ensure no components touch the ESC or exposed wires.

Seventh Step - Receiver and Sensors Installation

Flash the receiver with the necessary firmware before mounting and soldering.Mount the receiver in the rear of the frame. Insert its antennas into the antenna mount holes.

GNSS Module: Mount the GNSS module on a vibration-damped pad on a clear top surface of the frame, away from any magnetic or electronic interference sources like motors, power cables, or the ESC. Ensure a clear view of the sky for optimal GPS reception.

Barometer: If it's a separate unit, mount it in a location with good airflow but protected from direct wind gusts.

Differential Pressure Sensor (Airspeed Sensor): Ideally, mount the airspeed sensor facing forward in an area with clean airflow, avoiding turbulence caused by the propellers or the drone's body. Some airspeed sensors may have specific mounting recommendations, so refer to the sensor's manual for details.

IMU: The IMU is typically already integrated into the flight controller itself. If it's a separate unit, mount it rigidly to the frame in a location as close to the drone's center of gravity as possible.

Eighth Step - Receiver Soldering to Flight Controller

Solder the receiver's corresponding wires to the designated pads on the flight controller. The pads are labeled. Follow the scheme: GND, 5V, SBUS, SPORT to GND, 5V, SBUS, TX respectively.

Insulate the receiver with heat shrink tubing or tape. Insulate the soldered pads with hot glue.

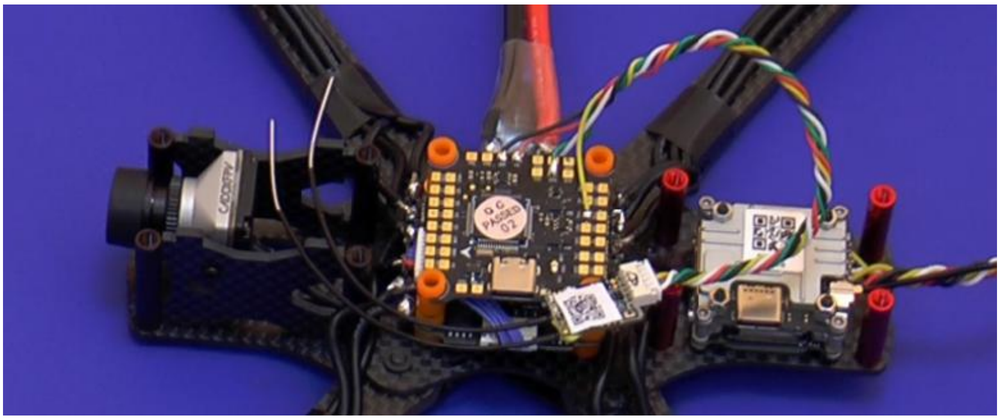


Fig. 4.7 Sensors Installation

Ninth Step - Wire Routing and Insulation

Bundle the cables together. You can also use sleeving. Insulate all exposed areas and secure the cables to prevent them from extending beyond the frame, being pinched, or obstructing buttons and connectors on the flight controller and video transmitter. Use hot glue to secure the cables after routing.

Tenth Step - Final Frame Assembly

Install and secure the top cover, and tighten the antenna straps. Install propellers after drone setup. Remove them for programming or adjustments.

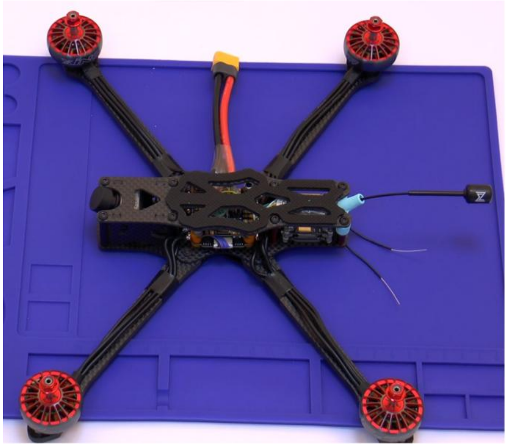


Fig. 4.8 Final Frame Assembly

Eleventh step Mounting a PWM (Full Metal Aluminum Alloy Claw)

Our Drone frame have mounting holes compatible with your gripper's base. We have gripper mounting hardware (refer to gripper's manual), screws or bolts appropriate for the frame's material.

Consider factors like center of gravity, gripper's reach relative to the propellers, and balance when choosing a mounting point on the drone frame. Ensure the chosen location provides enough clearance for the gripper's movement without interfering with other drone components.

Secure the gripper: Align the gripper's base plate with the desired location on the drone frame. Use the appropriate screws or bolts to fix the gripper base to the frame, ensuring a tight and secure connection. Tighten all screws securely.

Fig. 4.9 Full Metal Aluminum Alloy Claw

Connecting a PWM-controlled Gripper

The PWM cable comprises of three lines: power, ground and signal. A typical connector is shown in the image below:

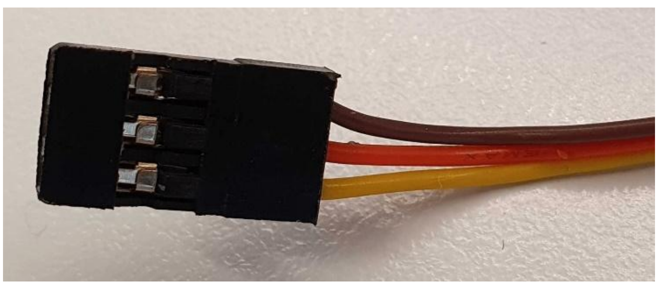


Fig. 4.10 Typical PWM connector

In the image above the wire colors have the following meanings:

Table 3. PWM cable purpose

Wire color	Purpose
Brown	Ground
Red	Power
Yellow	PWM Signal

We need to connect them into a PWM input of the Flight controller appropriately.

4.4 Ground Station

My ground station is a laptop computer running PX4-compatible software. This allows me to effectively control and manage unmanned aerial vehicles (UAVs) using the PX4 Autopilot.

Software installed on my laptop:

1. QGroundControl: This is a graphical user interface (GUI) for the PX4 Autopilot. QGroundControl allows me to plan flight paths, monitor UAV parameters, and track its position in real time.
2. MAVProxy: This is a command-line tool for managing the PX4 Autopilot. MAVProxy allows me to perform more complex tasks, such as configuring parameters and debugging code.
3. SITL (Software In The Loop): This is a simulator that allows me to test UAV software in a virtual environment. SITL is useful for developing and debugging new software without risking a real UAV.
4. OpenTX Companion: This software is used to update the firmware on my drone's control unit.
5. Betaflight Configurator: This software is used to configure the flight controller firmware.

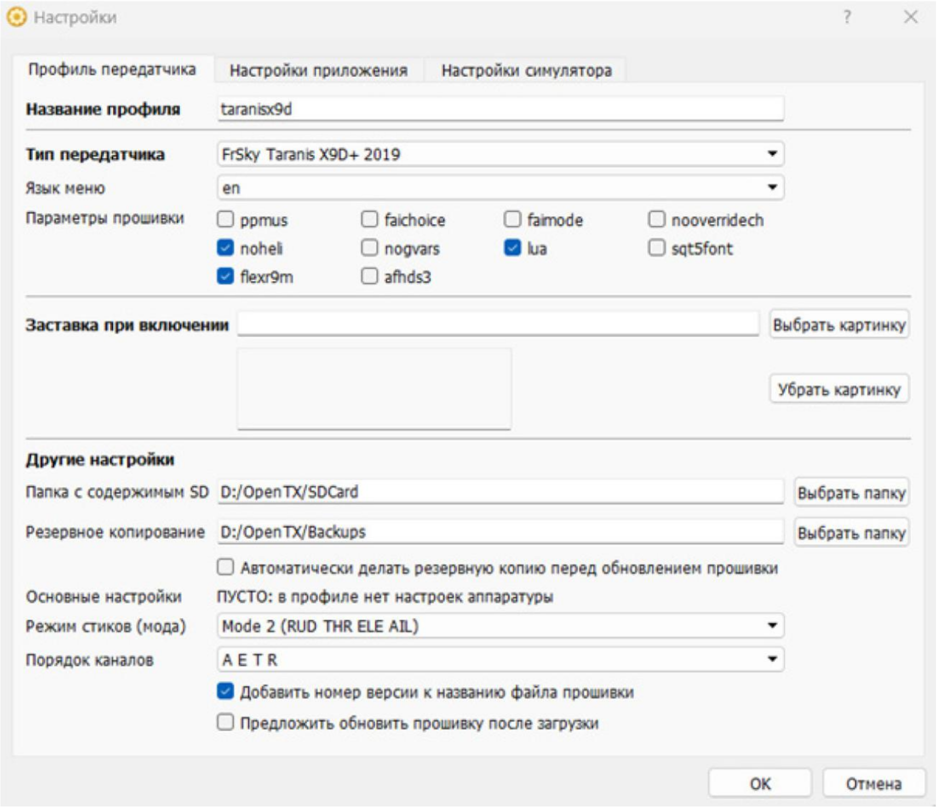
I Using my ground station to control a UAV with my ground station, I first connect the laptop to the UAV via a USB cable. Then I launch QGroundControl and select my UAV from the list of available devices. Once I am connected to my UAV, I can plan flight paths, monitor its parameters, and track its position in real time. I can also use MAVProxy to perform more complex tasks, such as configuring parameters and debugging code. I use SITL to test new UAV software in a virtual environment.

4.5 Hardware Setup

– Firmware and Control Unit Setup

First, let's update the firmware of our control unit.

The control unit we are using supports OpenTX firmware. To update the firmware, we will need OpenTX Companion. [7]



Название профиля taranisx9d

Тип передатчика FrSky Taranis X9D+ 2019

Язык меню en

Параметры прошивки
☐ ppmus ☐ faichoice ☐ faimode ☐ nooverridech
☑ noheli ☐ nogvars ☑ lua ☐ sqt5font
☑ flexr9m ☐ afhds3

Заставка при включении

Другие настройки

Папка с содержимым SD D:/OpenTX/SDCard

Резервное копирование D:/OpenTX/Backups

☐ Автоматически делать резервную копию перед обновлением прошивки

Основные настройки ПУСТО: в профиле нет настроек аппаратуры

Режим стиков (мода) Mode 2 (RUD THR ELE AIL)

Порядок каналов A E T R

☑ Добавить номер версии к названию файла прошивки

☐ Предложить обновить прошивку после загрузки

Fig. 4.11 OpenTX Companion

1. Connect the control unit to a computer or laptop without the drone.
2. Move the lower trims all the way down and hold down the power button. Connect the USB cable.
3. In the left panel, create a backup of the firmware.
4. Exit the menu and click "Update Transmitter Firmware" in the left panel.
5. Once the firmware is updated, disconnect the USB cable and exit the update menu on the control unit.

After the update procedure, it is recommended to check the Mode number.

1. To do this, go to "System Settings" and select the "Radio Setup" tab.
2. Scroll down to the bottom of the menu and find the Mode setting.
3. Set the value to 2.

After updating the firmware, it is highly recommended to calibrate the control unit sticks.

1. In the system settings, go to the "Hardware" tab and click "Calibration".
2. Follow the instructions on the screen.
3. Press Enter, move the sticks and side knobs to the middle position, then press Enter and move the sticks and knobs to the extreme positions (in a circle), then press Enter and exit.

A new model for our drone must be created in the control unit.

1. To do this, go to the "Menu", select a free slot and, holding down the Enter button, select "Create model".
2. In the model settings, you can set the settings for each individual model.

Next, let's bind the channels to the switches on the control unit.

1. To do this, go to the "Mixes" tab in the model settings and select a free channel.
2. Holding down Enter, enter the channel settings and select the switch you want to bind to the channel under Source.
3. Now you can use the selected switch to change the values on the channel. This can be used, for example, to turn on the drone motors and other functions.

Receiver and Control Unit Binding Procedure

Bind is the procedure for binding the receiver and the control unit. By default, the receiver and transmitter do not know about each other, and therefore they need to be configured to work on the same frequency.

To connect the receiver to the control unit, go to the control unit.

1. Go to the "Setup" tab in the model menu.
2. Under Interanl RF, select Mode - MULTI, Type - receiver protocol (in our case FrSky X) and Subtype - D16.
3. Then press Bind under Receiver. Our transmitter has gone into Bind mode.
4. Next, on the receiver, hold down the Bind button (usually the only button on the receiver and is the bind button) and connect the power. For safety reasons, only connect the power without propellers at first! You can release the bind button. The speaker on the control unit should stop beeping.

5. Disconnect the power from the receiver and reconnect it. The signal indicator should appear on the control unit. The receiver and control unit are linked.

4.6 Software Setup

After completing the hardware setup of all drone components, you can proceed to configuring the flight controller firmware. Configuring the flight controller software is one of the most important steps, as it is in the flight controller that the drone's flight scenarios are set.

– Software Preparation

For our flight controller, we will use the popular open-source firmware Betaflight. The firmware supports a large number of flight controllers, including ours. To get started, you need to install the Betaflight Configurator configuration program. After installing the program, you need to carefully read the information in the main program window and install the necessary drivers.

– Updating Flight Controller Firmware

To flash the flight controller firmware, you will need the drone itself with a Betaflight-compatible flight controller, a USB cable, and a computer with internet access (to download the latest firmware). To update the firmware, go to the "Flash" tab. Connect the laptop's USB to the flight controller. If you are on the "Flash" tab, the flight controller will automatically switch to DFU mode. In the first drop-down list, select your flight controller, and in the next list, select the latest firmware version.

In the Build Configuration window, select "SMARTPORT" in the Telemetry Protocol setting.

Click "Download Firmware". The firmware will be downloaded from the internet. After the firmware is downloaded, click "Flash Firmware" to flash the flight controller.

Then click the "Connect" button to go to the configuration mode.

– Configuring the Flight Controller

The first tab, "System", shows information about the orientation of the flight controller. It is important to make sure that the flight controller is installed correctly. That is, the tilts of the drone in reality should correspond to the tilts of the drone on the configurator screen. If the tilts do not correspond to the real ones, this can be changed in the "Configuration" tab. You can also calibrate the accelerometer and compass here. The information about flags prohibiting ARM, voltage and current, as well as data about the quality of the connection is also located here.

The "Ports" tab presents a window for configuring the flight controller ports. This window configures all peripherals connected to the flight controller: receivers, video transmitters, etc. Select Serial Rx on the port to which your receiver is connected, on many flight controllers SBUS is connected to the second port, the exact port number can be found in the instructions for your flight controller.

Identifier. This column indicates the ports available on the PC. Configuration/MSP. As the name suggests, it is usually used to communicate with peripherals at a lower level using MSP (MultiWii serial protocol). Here you can also set a specific baud rate for this protocol.

Serial RX. Used to configure UART to receive serial data from the receiver. This is the most common use of the UART port.

Telemetry Output. Here, the telemetry transmission protocol is selected and the PC on which port it will operate is specified.

Sensor Input. Here we tell the flight controller which sensor will be used on this port. For example, if you are using GPS, then you should specify it here.

Peripherals. Here, peripherals that should be controlled by the flight controller are specified. For example, to control a video transmitter.

Next, select the MSP configuration opposite UART6, and in the "Peripherals" tab select VTX (MSP + Displayport) from the drop-down menu. On the "Telemetry Output" tab, select "SmartPort" from the drop-down list opposite the UART to which the S.Port was connected on the receiver.

The "Configuration" tab contains the main functions of the flight controller, such as enabling sensors and their operating frequencies, functions related to the operation of peripherals, and here you can also configure the location of the controller board, for example, if you installed it not in accordance with the nose of the copter.

The "Power and Battery" tab is responsible for the settings of the drone's power sensors. Here you can select the power data source and set the voltage and battery capacity settings. Leave the default voltage settings per bank and enter the information about the capacity of your battery. It is also strongly recommended to perform the calibration procedure for the voltage sensor and current sensor.

Using the "Presets" tab, you can save and load ready-made settings for firmware parameters, as well as download ready-made small files with pre-installed settings from other pilots and test them on your drone.

The "PID Settings" tab, as you might guess, is responsible for the PID controller settings. Here, the settings and parameters of PID profiles, Rate and filter settings, as well as throttle curve settings are set.

Next, the receiver settings are set in the "Receiver" tab. Here you can select the method of connecting the receiver to the flight controller, specify whether to use telemetry to transmit information about the state of the drone.

4.7. Mission Planning Methods

Let's explore the methods for creating drone flight missions using ground control station software and configurators.

Since a flight controller equipped only with a gyroscope and accelerometer cannot enable the drone to maintain a single position in space, a GPS module is required for stabilization, access to flight mission planning, and autonomous flight. Currently, some of the most popular GPS modules are the Beitian BN-180 and Beitian BN-220. These modules are connected to the flight controller via a UART (Universal Asynchronous Receiver-Transmitter) interface. It is important to note that the RX (Receiver) of the GPS module should be connected to the TX (Transmitter) of the flight controller, and the TX of the GPS module to the RX of the flight controller.

Flight Mode Configuration

Accessing Additional Flight Modes with GPS

The integration of a GPS module unlocks additional flight modes for your drone. These modes can be configured in the "Modes" tab.

ALTHOLD (Altitude Hold): In this mode, the drone maintains a constant altitude, controlled by the throttle stick. For this mode to function, a barometer is required on the flight controller.

POSHOLD (Position Hold): This mode enables the drone to maintain its current position in space. Position adjustments are achieved using the control sticks.

RTH (Return to Home): This mode initiates the drone's return to its home point. The home point is the location where the drone was armed.

WP (Waypoint): This mode executes a pre-planned mission, guiding the drone through a sequence of waypoints.

PX4 and Ardupilot Autopilots

Drone flight controllers are constantly evolving, and as they develop, the task of creating advanced autopilot systems arises.

Such systems should include:

- A full set of onboard sensors, including not only a gyroscope and accelerometer, but also a barometer and magnetometer;
- A wide range of I/O ports for connecting peripherals;
- High-quality software for control and easy access to all autopilot functions.
- UAV flight controllers should be versatile for use with different types of aircraft.

Popular types of autopilots such as PX4 and Ardupilot have such functions. For the average user, the difference in choosing an autopilot is not great, but Ardupilot has more features.

PX4 and Ardupilot are open source autopilot systems for autonomous UAVs. To use these systems, more advanced flight controllers are required.

A flight controller for an autonomous UAV must have a set of sensors on board, such as a gyroscope, accelerometer, barometer, and magnetometer. Pixhawk flight controllers have been specially developed for these autopilots. As well as for small mini-drones, a GPS module is required for automatic flight.

Connecting drone gripper to PX4. [8]

Enabling Gripper Support:

PX4's gripper support is linked to the "package delivery" feature, which needs to be enabled first.

In the PX4 parameters, set the PD_GRIPPER_EN parameter to 1 (this might require a reboot after the change).

Setting Gripper Type:

PX4 offers support for various gripper types. Set the PD_GRIPPER_TYPE parameter to the specific type of gripper you're using (Servo).

Testing the Gripper:

Ensure your drone is on a bench with propellers removed for safety reasons.

Within the QGroundControl (QGC) MAVLink Shell, run the payload_deliverer gripper_test command.

PX4 should provide feedback on the test. If you encounter an error message like "[payload_deliverer] not running," revisit the setup procedures.

If the test runs successfully, you can use the joystick in QGC to trigger opening and closing actions of the gripper to verify functionality.

You can manually trigger a gripper manually from a Joystick button if you've mapped gripper open and gripper close buttons in the QGC Joystick Configuration. Note that if you press the Grab button while the gripper is opening, it will automatically abort releasing behavior and go to the closed position, effectively cancelling the release command. If you do this in a mission while the release is actually happening, then the delivery will be cancelled.

Manually triggering a gripper from an RC Control switch is not supported.

MAVLink applications, such as ground stations, can also control the gripper using the MAV_CMD_DO_GRIPPER MAVLink command.

4.8 Mission Planning

A package delivery mission is planned in much the same as any other waypoint mission, with mission start, takeoff waypoint, various path waypoints, and possibly a return waypoint. The only difference is that a package delivery mission must include a mission item that indicates whether the package should be released on the ground (Land) or in-air (Waypoint), followed by another mission item to deploy the package (Gripper Mechanism).

Whether or not you Land depends on whether the package can safely be deployed while flying, and if the vehicle is capable of landing at the deployment location. Since a gripper cannot lower packages safely, multicopter and VTOL vehicles will often land to deploy packages when using a gripper.

After the deployment device indicates completion, the vehicle will proceed to the next waypoint. Note that if landed, the next mission item after deployment should be another Waypoint or a Takeoff mission item (it must not be a RETURN.)

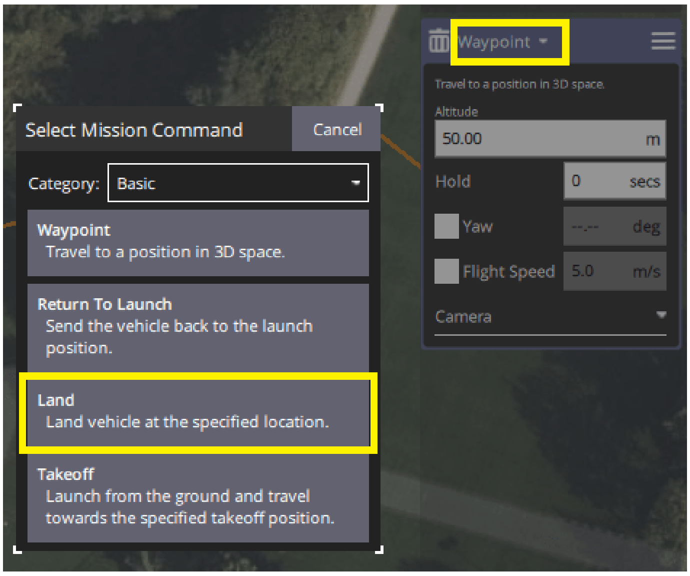
Creating a Package Delivery Mission

To create a package delivery mission (with a Gripper):

1. Create a normal mission with a Takeoff mission item, and additional waypoints for your required flight path.

2. Add a waypoint on the map for where you'd like to release the package.

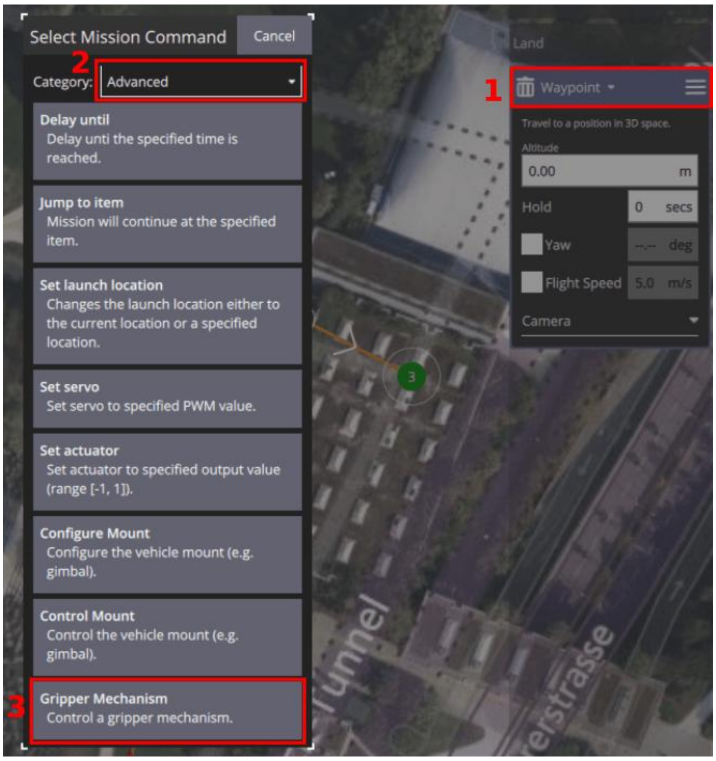
- To drop the package while flying set an appropriate altitude for the waypoint (and ensure the waypoint is at a safe location to drop the package).
- If you'd like to land the vehicle to make the delivery you will need to change the Waypoint to a Land mission item. Do this by selecting the mission item heading, then selecting Land in the popup dialog.



Travel to a position in 3D space.
Altitude 50.00 m
Hold 0 secs
Yaw --.-- deg
Flight Speed 5.0 m/s

Fig. 4.12 Selecting drop waypoint

3. Add a waypoint on the map (anywhere) for the gripper release. To change this to a Gripper Mechanism select the "Waypoint" heading, and in the popup changing the group to "Advanced", then selecting Gripper Mechanism.



Select Mission Command

Category: Advanced

Delay until
Delay unti the specified time is reached.

Jump to item
Mission will continue at the specified item.

Set launch location
Changes the launch location either to the current location or a specified location.

Set servo
Set servo to specified PWM value.

Set actuator
Set actuator to specified output value (range [-1, 1]).

Configure Mount
Configure the vehicle mount (e.g. gimbal).

Control Mount
Control the vehicle mount (e.g. gimbal).

Gripper Mechanism
Control a gripper mechanism.

Waypoint

Travel to a position in 3D space.

Altitude: 0.00 m

Hold: 0 secs

☐ Yaw: --.-- deg

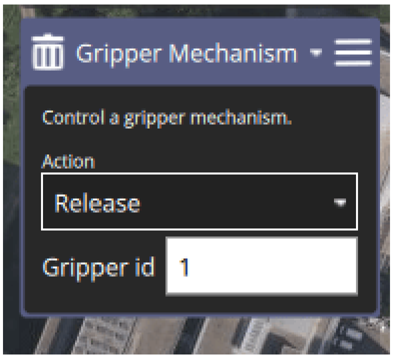
☐ Flight Speed: 5.0 m/s

Camera

Fig. 4.13 Gripper settings

4. Configure the action for the gripper in the editor.

- Set it to "Release" in order to release the package.
- The gripper ID does not need to be set for now.



Gripper Mechanism

Control a gripper mechanism.

Action: Release

Gripper id: 1

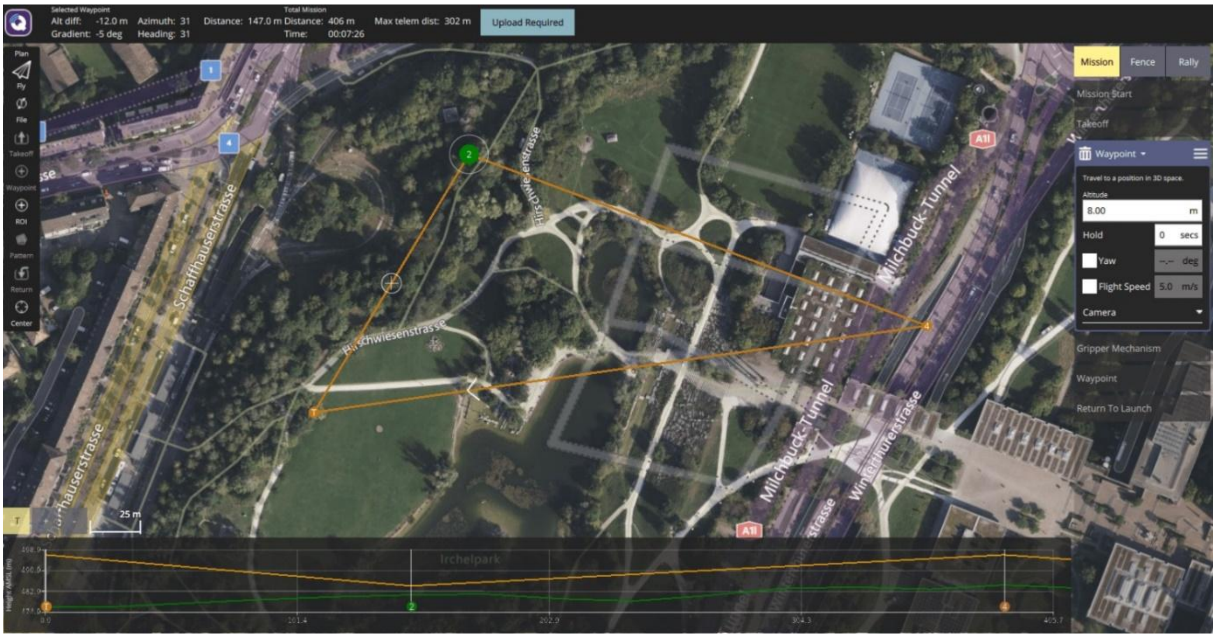
Fig. 4.14 Gripper release settings

5. Add additional waypoints for the remainder of the path. If you landed, then remember that you must include a waypoint after the Gripper Mechanism before adding a Return mission item.

4.9 Example Plans

Package Drop Mission

This shows a mission plan where the vehicle drops the package while flying. The initial mission item is a waypoint and the action is a Gripper Release (shown in mission item list)



Selected Waypoint
Alt diff: -12.0 m Azimuth: 31 Distance: 147.0 m
Gradient: -5 deg Heading: 31

Total Mission
Distance: 406 m
Time: 00:07:26
Max telem dist: 302 m

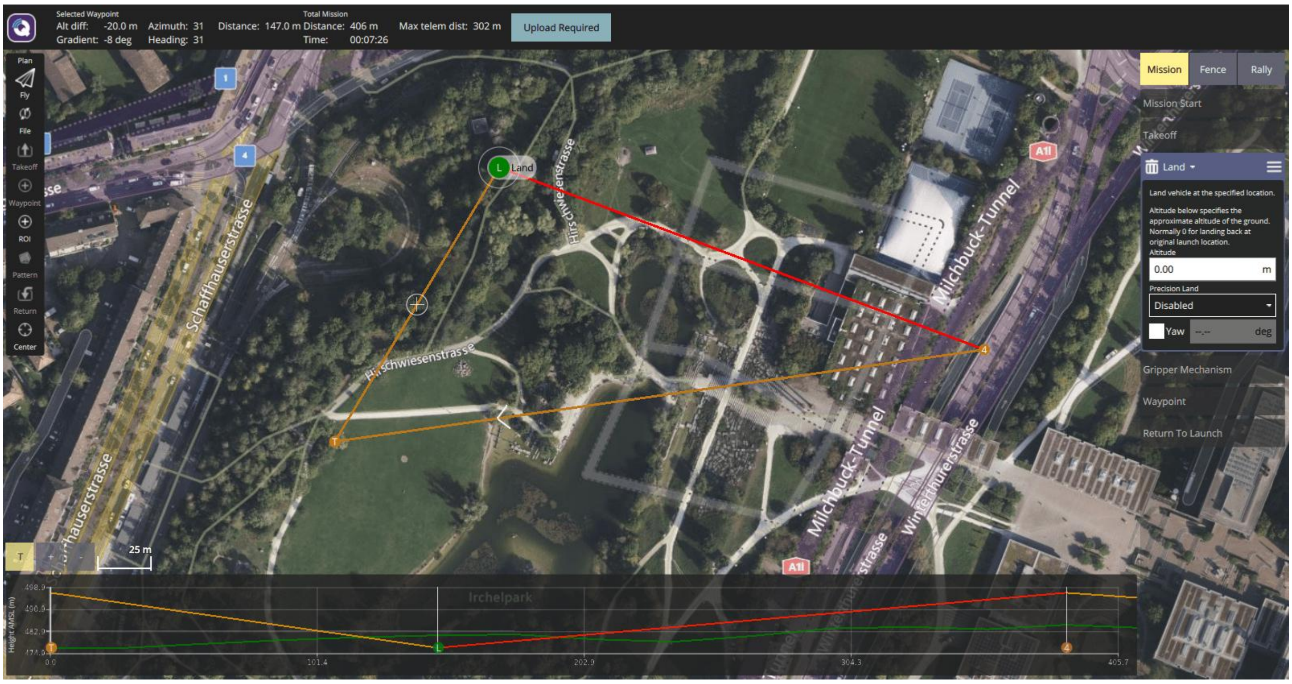
Waypoint
Travel to a position in 3D space.
Altitude: 8.00 m
Hold: 0 secs
☐ Yaw: --.-- deg
☐ Flight Speed: 5.0 m/s
Camera

Fig. 4.15 Package Drop Mission

Note how the altitude graph shows the pre-waypoint as an in-air waypoint, also on the right panel.

Land and Release Mission

This shows a mission plan that where the vehicle lands to deliver the package.



Selected Waypoint
Alt diff: -20.0 m Azimuth: 31 Distance: 147.0 m
Gradient: -8 deg Heading: 31

Total Mission
Distance: 406 m
Time: 00:07:26
Max telem dist: 302 m

Land
Land vehicle at the specified location.
Altitude below specifies the approximate altitude of the ground. Normally 0 for landing back at original launch location.
Altitude: 0.00 m
Precision Land: Disabled
☐ Yaw: --.-- deg

Fig. 4.16 Land and Release Mission

Note how the altitude graph shows the Land item.

Chapter 4 conclusion

This chapter provided a comprehensive and meticulously detailed roadmap for assembling, configuring, and operationalizing a cargo delivery drone. The chapter systematically outlined the hardware setup process, ensuring seamless communication between the control unit, receiver, and flight controller. This critical phase encompassed crucial procedures such as firmware updates for optimal performance and control stick calibration for precise maneuvers.

Chapter delved into the intricacies of flight controller software configuration, empowering me to unlock the drone's full potential. It explored the critical parameters governing motor behavior, sensor data interpretation, and flight mode activation. This in-depth exploration equips users with the knowledge to fine-tune the drone's performance for specific delivery missions, prioritizing agility for maneuvering in confined spaces or maximizing flight time for long-distance deliveries.

The chapter also shed light on the transformative potential of integrating a GPS module. This critical component unlocks advanced flight modes like altitude hold and return to home, significantly enhancing mission safety and efficiency. These functionalities offer substantial benefits, particularly in scenarios with unexpected signal interference or strong winds. With return-to-home mode activated, the drone can autonomously navigate back to its starting point, safeguarding both the payload and the surrounding environment.

Finally, the chapter culminated with a detailed exploration of mission planning using ground control station software. I was guided through the meticulous process of charting a course by creating waypoints, strategically selecting drop zones, and configuring the gripper mechanism for efficient payload release. This newfound ability to pre-program flight paths paves the way for autonomous deliveries, minimizing human intervention and maximizing operational efficiency.

By successfully navigating the crucial steps outlined in this chapter, I have gained the necessary knowledge and expertise to transform a collection of components into a sophisticated aerial delivery system.

GENERAL CONCLUSION

This diploma thesis presents a comprehensive investigation into the potential of drone delivery systems to revolutionize the landscape of goods delivery. Through meticulous research, I explored the intricate interplay between technological advancements, burgeoning market demands for faster and more convenient deliveries, and the ongoing challenges faced by this nascent field. These challenges encompass limitations in current drone technology, a complex regulatory environment that needs to evolve, and ethical considerations surrounding drone usage.

My research yielded a significant contribution to the field by identifying short-range helicopter drones as the most strategically viable option for near-term adoption. This conclusion is grounded in a rigorous analysis of various delivery drone models, highlighting the compelling advantages of short-range helicopter drones. Their market relevance aligns perfectly with the increasing demand for swift and efficient delivery within urban and suburban areas. Furthermore, advancements in battery technology, electric motors, and miniaturization make them technologically feasible, striking a balance between payload capacity, flight time, and operational cost. Additionally, their ability to integrate seamlessly with existing infrastructure minimizes disruption to the environment.

To establish a robust theoretical foundation for future drone control system design, I meticulously constructed a mathematical model for a quadcopter. This model, drawing upon established principles of physics like Newton's and Euler's laws, provides a valuable framework for further analysis and control system optimization. It serves as a significant contribution to the field, potentially leading to increased efficiency and reliability of drone delivery systems.

However, my exploration extended beyond theoretical understanding. To bridge the gap between theory and reality, I actively translated this foundation into a tangible application. This hands-on endeavor involved meticulous hardware setup, ensuring seamless communication between the control unit, receiver, and flight controller. Furthermore, I delved into the intricate configuration of flight controller software, empowering the drone to unlock its full potential by manipulating critical parameters governing motor behavior, sensor data interpretation, and flight mode activation. Finally, I mastered mission planning using ground control station software, a crucial skill that allows for pre-programmed flight paths and paves the way for autonomous deliveries and minimized human intervention. Through this comprehensive process, I cultivated the technical knowledge and practical skills necessary to transform a collection of components into a functional aerial delivery system.

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