BACHELORTHESIS
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Conception and Development of a Quadcopter UAV for Delivery Tasks

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Conception and Development of a Quadcopter UAV for Delivery Tasks

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Thema der Arbeit

Konzeption und Entwicklung eines Quadcopter UAV für Lieferaufgaben

Stichworte

UAV, Quadcopter, PX4, Drohne, Starrflügel, Rotationsdrohne, Roll, Pitch, Yaw

Kurzzusammenfassung

Diese Bachelorarbeit diskutiert den Entwurf, die Entwicklung und die Validierung eines Drohnensystems, das in der Lage sein soll, Lieferaufgaben kleiner Artikel auszuführen. Die Vorgehensweise beinhaltet die Recherche sowohl bestehender Literatur als auch aktueller Drohnentechnologie. Basierend auf bestimmten Anforderungen und Vorschriften wird eine Lösung zur Erreichung des Ziels ausgewählt. Darüber hinaus werden weitere Untersuchungen zu möglichen Softwareansätzen durchgeführt. Abschließend erfolgen Entwicklungen und Tests der Gesamtlösung mithilfe verschiedener Hard- und Softwaretools.

Moutaz Radwan

Title of Thesis

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Keywords

UAV, Quadcopter, PX4, Drone, Fixed-wing, Rotary-wing, Roll, Pitch, Yaw

Abstract

This thesis demonstrates the design, development, and validation of a drone system capable of performing delivery tasks of small items. The strategy involves research of existing literature and current technology of drones. Based on a specific set of requirements and regulations, a solution is selected for achieving the goal. Moreover, further investigation about possible software approaches is done. Finally, development and testing of the overall solution are conducted using various hardware and software tools.

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1 Introduction

1.1 Motivation

In recent years, the world's technology has been developing in many aspects at a high pace. One of the several, lately quickly evolving, fields to expand more in the future is the field of drone-type unmanned aerial vehicles (UAV). Drones have a large impact on the industrial needs in various fields, e.g., entertainment, parcel transportation, agriculture, and plant protection. As stated by the predictions of the International UAV Association, the drone market will have a total economy reaching 82.1 billion US dollars by the year 2025. [46]

The focus of this paper discusses the possibility of an autonomous parcelcopter system. Companies including Amazon, Google, Wingcopter, and DHL have conducted a practical test of drone delivery, demonstrating the technology's promise as a future replacement or addition to conventional delivery methods. [36] Approving and applying delivery drones in everyday-life transportation could significantly transform the industry's shape. This leads to reducing the number of needed drivers, fossil fuel-powered delivery vehicles, and ground and aerial traffic. Additionally, an improvement in road safety, accessibility to poorly-constructed areas, and saving delivery time will be noticed. [22]

1.2 Thesis goal

The goal is to build a stable drone system that is able to deliver a suitable item from a specific location to another destination location. Different solutions are to be investigated carefully and compared until the appropriate system is selected. Also, the software supported by the drone's flight management unit is an essential element in the investigation process. Finally, the complete developed drone gets the to-be-delivered payload attached, takes off and proceeds to the specified waypoint, prepares to descend to a predefined distance above the ground, and lastly, drops the payload and land.

1.3 Work Description/Topics Discussed

This paper consists of the following chapters where each aspect of the work is discussed.

- **State of Art:** This chapter provides investigation results about the current status of the drone industry, how far the technology has reached till the present, and what drones are out in the market including commercial and DIY drones. It also includes theoretical background, relevant concepts, and definitions.
- **Requirements:** This chapter discusses and analyzes the functions and different types of requirements the system must have such as performance requirements or environmental requirements. It also includes any constraints or regulations the drone must comply with.
- **Conception:** Based on the requirements determined in the previous chapter, an analysis, and comparison of potential drones are carried out to select the appropriate solution. Moreover, the decided hardware and software solution is discussed in more detail from different aspects to validate how it meets the thesis's objectives.
- **Development:** Here the overall architecture of the system and components are demonstrated. The design process and implementation approach are discussed along with the used software frameworks and tools. Also, any necessary development environment or setup is mentioned.
- **Validation:** This chapter shows how testing the system is performed, which evaluation tools and procedures are used, and the final resulting system with its capabilities, weaknesses, and possible improvements. It explains how the results meet the requirements or what impediments were encountered during the development.
- **Summary:** This chapter gives a summary of the research problem and goal. It provides a brief discussion of the main topics, points, issues, and results addressed in the thesis.
- **References:** This section states the sources of information provided in this paper.

2 State of Art

For pursuing the goal, the current drone technology, similar solutions, and available approaches that can be beneficial for the research are to be investigated to have a better and clearer idea about how far the drone technology reached and the current capabilities available on the market. On the one hand, there are commercial drones out in the market that are either dedicated to a specific purpose or versatile. On the other hand, various Do-it-yourself (DIY) drone kits are available for development and are flexible to be programmed as needed. These may be suitable candidates for the decision-making phase.

2.1 General Terms and Concepts

Most technologies are usually described with different and vague terminology. A car for example, which is called automobile as well, used to have the term "horseless carriage" when first invented. The same applies to UAVs. The term "drones" has had dislike among different societies. So, due to the inconsistency in referring to these systems through, e.g., organizations and researchers, various alternatives currently exist. Examples are “unmanned aircraft system” (UAS), “unmanned aircraft vehicle” (UAV), “remotely piloted aircraft” (RPA), and “remotely operated aircraft” (ROA). [43]

2.1.1 UAV Categorisation

Mainly, UAVs are classified into two forms: fixed-wing and rotary-wing. There are also hybrid UAVs whose designs can have a mix of both. In terms of shape and structural resemblance, the fixed-wing types are similar to airplanes and referred to as horizontal takeoff and landing (HTOL) vehicles while the rotary-wing drones operate similarly to helicopters and are considered vertical takeoff and landing (VTOL) systems. See **Figure 2.1** for demonstration. VTOL UAVs dominate the market due to their ability to generate lift power vertically in a stationary state, unlike HTOL drones that need more space and runways because movement thrust is necessary for the take-off. However, HTOL vehicles can generally last for a longer time or have higher speeds as they need less power compared to VTOL vehicles. [43]

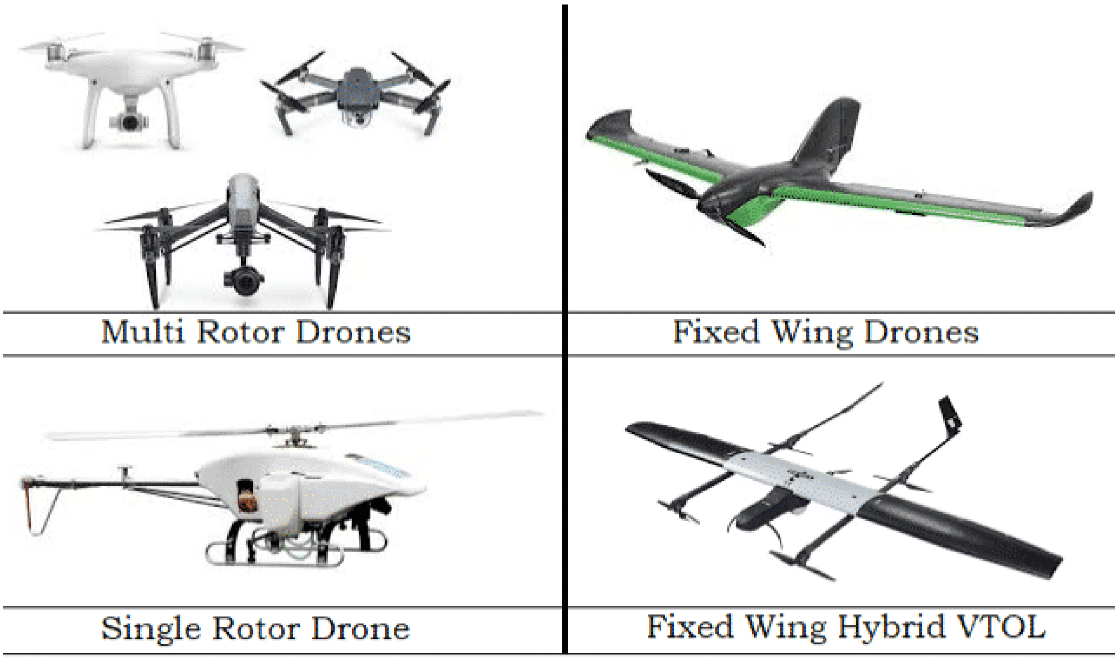

Figure 2.1: UAVs Classification. [17]

2.1.2 Working Principle (Drone Dynamics)

The control of UAVs is relatively more complicated than ground vehicles since the motion is controlled along three axes. The movement directions are classified into three types: along the X-axis is "roll", along the Y-axis is "pitch", and along the Z-axis is "yaw" as illustrated in **Figure 2.2**.

In a quadcopter, the four propellers are normally designed and placed symmetrically and each rotor is controlled independently for better balance and movement flexibility. Depending on the speed and rotating direction of each propeller, the drone's movement direction is decided. [18] Check **Figure 2.3** for an overview of the drone control techniques.

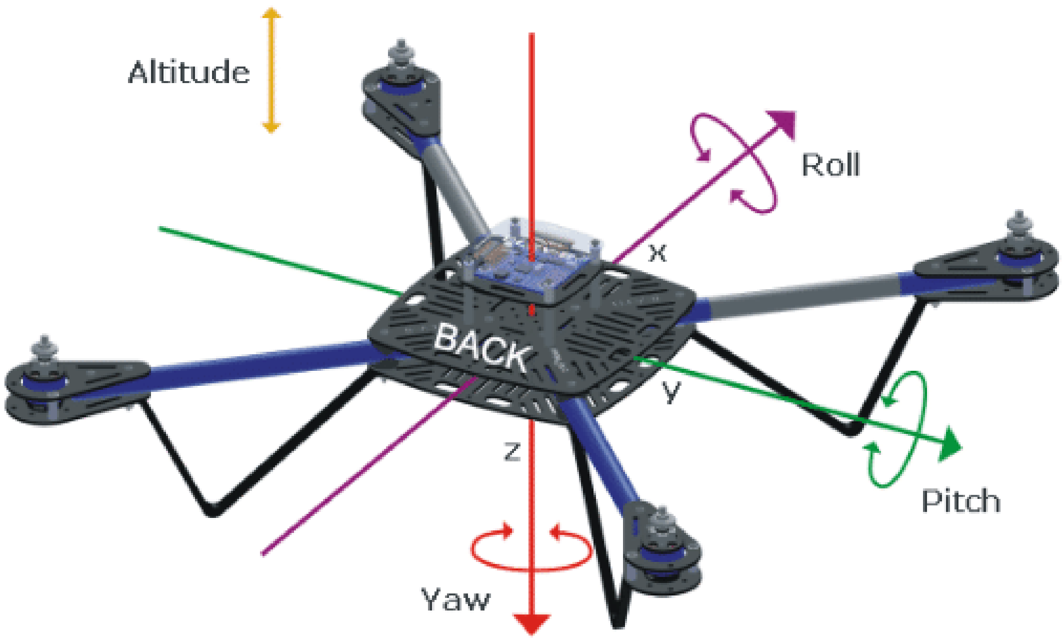

Figure 2.2: Directions of Drones' Movement. [18]

2.1.3 Components

As mentioned earlier, rotary-wing UAVs dominate the market and hence, the necessary components that VTOL drones must have, are discussed here. Other optional components, e.g., extra vision sensors are not covered here.

- **Frame:** The frame, also called "Chassis", is the housing of the main electronic components. It decides the drone structure from shape, size, and weight. Materials like carbon fiber are commonly used to build the frame due to their light-weight and durable features. [43]
- **Propeller:** The propeller is mounted on the end of each frame arm and consists of rotating blades. The propeller characteristics depend on the number and size of the blades. Apart from weather influences, e.g., wing speed, the propeller's thrust relies on its speed. [43]
- **Motor:** Each motor's shaft is attached to each propeller. The motor gets the required electrical power to turn it into torque power on the shaft. This energy must be enough to control the corresponding propeller. [43]

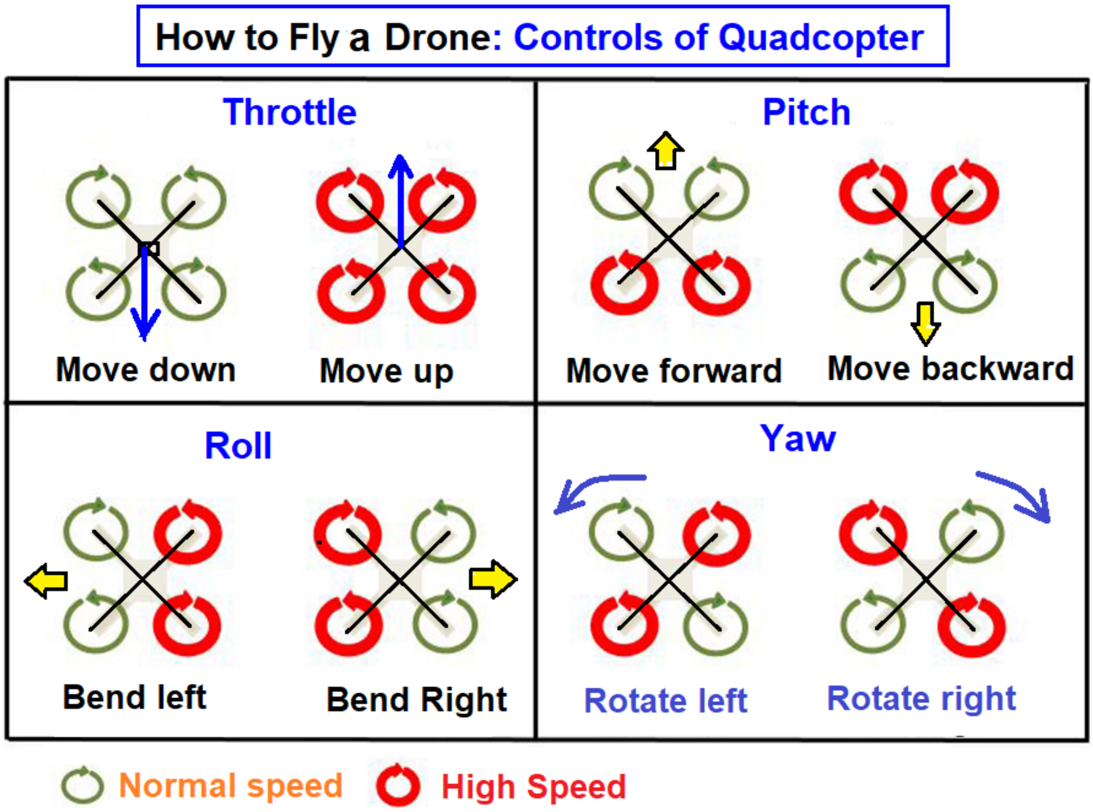

Figure 2.3: Controls of Quadcopters. [17]

- **Electronic Speed Controller (ESC):** For each motor, there is a separate ESC responsible for adjusting the motor speed by providing the exact needed current from the battery to the motor through a power distribution board (PDB). [43]
- **Power Distribution Board:** PDB is a board that basically provides electricity to power up the flight controllers and the other components. It controls how the power provided by the battery is regulated depending on the components' needs. [43]
- **Flight Controller:** The flight controller or flight management unit (FMU) is the brain of the system. It translates input data with an algorithm and outputs the decision to the system components. These input data can be high-level commands from a human-operated RC controller or embedded software programs. Additional data are also collected from on-board sensors. [43]

- **Battery:** The battery is the source of electric power and is connected to the PDB to provide the UAV's electric components with the required current and voltage. Batteries' capability is described by capacity (mAh) and charging/discharging rate (C-rate). Assuming constant voltage, the capacity is like a compromise between longer battery time and a higher amount of current provided. The C-rate decides that as it describes the usage per hour. 1C rate means the current of specified "mA" is consumed in 1 hour. 2C is double rate, so 2x"mA" is discharged in 30 minutes, and so on. [43]

The components can be assembled together in different ways. **Figure 2.4** shows an example of a possible setup.

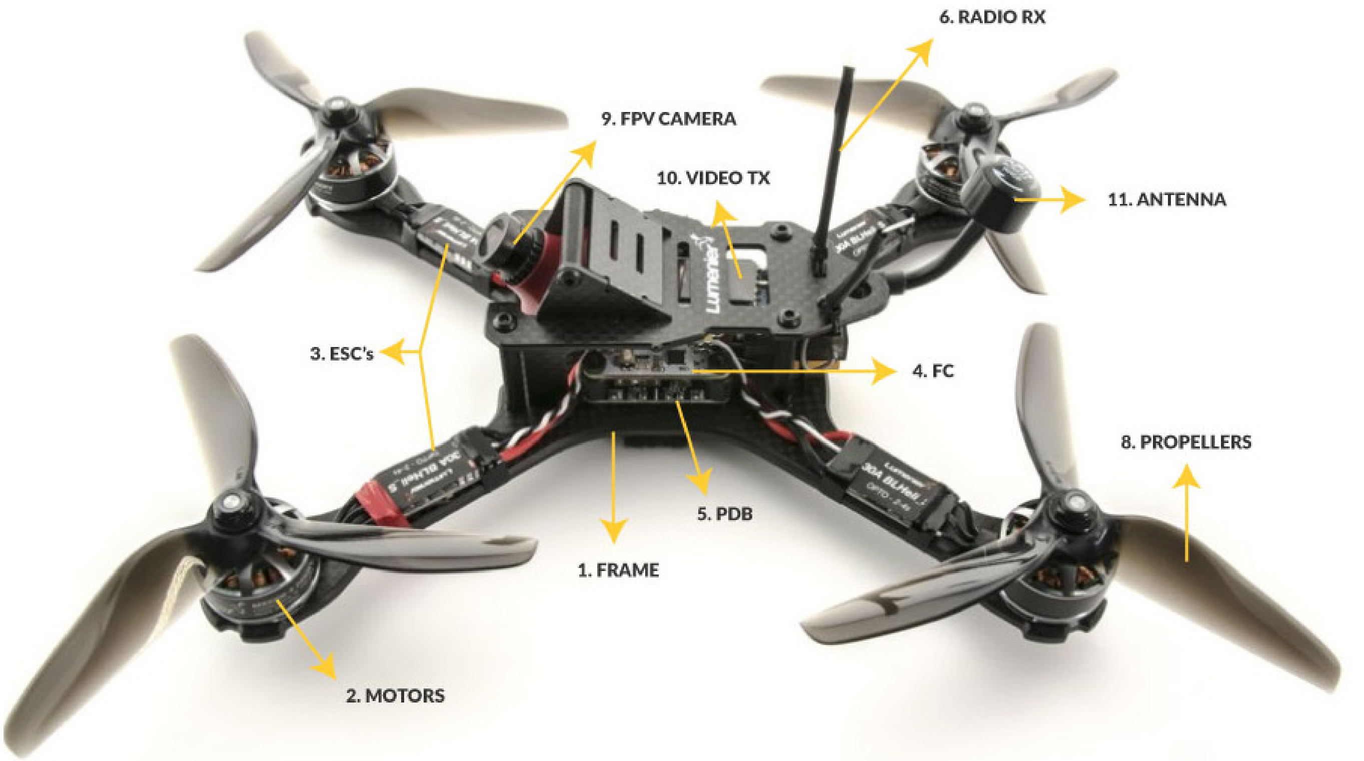

Figure 2.4: Quadcopter Components. [23]

2.2 Commercial Drones

The term "commercial drones" is applied to unmanned aerial vehicles used in business and for industrial purposes. These drones have dedicated functionalities and are built with the necessary equipment for handling complex and specific tasks. For safety and possible improvements, drones are remotely controlled and monitored from ground stations by trained and professional operators. [15] Examples for such UAVs are shown in **Figure 2.5**.

(a) Matternet M2 [9]

(b) Wingcopter 198 [44]

(c) Zipline Delivery [21]

(d) DHL Parcelcopter [24]

Figure 2.5: Commercial Delivery Drones examples

2.2.1 Matternet M2 V7 Quadcopter

The Matternet M2 V7 quadcopter drone is authorized by the Swiss Federal Office for Civil Aviation (FOCA) for full logistics operations over different cities. It is designed to bear a payload capacity of up to 2 kilograms with a max size of 4 liters over distances of up to 20 kilometers. [9]

The M2 V7 quadcopter is a multi-rotor Unmanned Aerial Vehicle capable of flying with a speed of 10m/s. This drone has extra features, such as automatic payload and battery-exchange ability, intelligent routing and monitoring, precise landing, and intuitive command and control. [4][40]

According to [4] and [40], the drone specifications are the following:

- **Application:** Delivery of goods or emergency supplies.
- **Weight:** Empty weight (with battery): 9.5 kg.
- **Flight time:** 15-30 minutes depending on cargo and conditions.
- **Safety:** In the event of a crash, UAVs may result in injuries or property damage. Therefore, a parachute was included in the drone's design to ensure a secure landing. Additionally, it is built with precision landing and encrypted communications for additional security.
- **Replacement components:** Replacement components can only be obtained from the manufacturer.
- **Delivery method:** Automated ground station.

2.2.2 Wingcopter 198

The Wingcopter 198 is an electric tilt-rotor vertical take-off and landing (VTOL) that can bear 25 kg maximum take-off mass (MTOM). This wingcopter has two operation modes depending on the flying status, Multicopter, and Fixed-Wing modes. It is able to cruise with a max speed of 40 m/s in the fixed-wing mode. [44]

Normally, delivery drones follow the principle of loading, flying, and unloading. But because of the simple unloading mechanism and limited space, most drones, after going to the recipient, come back empty. To improve efficiency, the German drone manufacturer Wincopter has presented its delivery drone system that is able to supply three separate destinations on just one flight (triple drop). [13]

According to [44] and [13], the drone specifications are the following:

- **Application:** Packages delivery.

- **Payload:** Up to 6 kg total payload, max. 5 kg with triple drop.
- **Weight:** 20 kg with batteries.
- **Range/Flight time:** See **Figure 2.6**

Range Estimation

Payload	5 kg	4 kg	3 kg	2 kg	1 kg	0 kg
Direct one-way flight	75 km	80 km	85 km	90 km	95km	110 km
	40 min	45 min	50 min	55 min	60 min	70 min
Flight with 1x slow drop or 1x intermediate landing	65 km	70 km	75 km	80 km	85 km	95 km
	35 min	40 min	45 min	50 min	55 min	60 min

Considering ideal conditions (no wind, sea level altitude, 15°C air temperature) and ideal operation (ideal cruise speed, 20% battery reserve, standard payload form factor)

Figure 2.6: Wingcopter covered Range estimation. [44]

- **Safety:** It has a set of navigation lights, horizontal and vertical awareness system, and a LiDAR ground altimeter.
- **Package mounting:** On ground using quick connect adapter & package protection by heat shrink foil.
- **Delivery:** On ground or slow drop using winches.

2.2.3 Zipline Drone

The company Zipline builds and produces its own drones, the same for building and operating its distribution centers which could be considered as a drone airport. [5] These drones are fixed-wing, designed and assembled at Zipline's headquarters in Half Moon Bay, California.

This UAV can fly at a speed of up to 128 km/h and above sea level till 120 m. To have a brief idea about the strategy followed here, the drone takes off after an operator loads the medical supplies and performs the necessary checks. Leaving the distribution center, the drone is programmed to go to its specified delivery location. Meanwhile, pilots in all distribution centers manually monitor the drones in process. Arriving at the delivery site, the drones unload the special packaging using a parachute technique. For quickly managing as many orders as possible, a fast-replaceable battery is used. [26][47]

According to [26] and [47], the drone specifications are the following:

- **Application:** Delivery of vaccines, Medicines, Essential medical products, and safe blood.
- **Payload:** Up to 1.75 kg.
- **Weight:** 10 kg.
- **Range:** Up to 160 km.
- **Safety:** All flights are coordinated with the Rwandan Civil Aviation Authority. All of the flight systems and hardware have built-in redundancies as well as an emergency parachute landing system in case of failure.
- **Delivery method:** Packages are loaded manually inside the drone and then unloaded with a parachute into the destination zone.

2.2.4 DHL Parcelcopters

DHL had a series of different delivery drones in their industry. The latest technology is the Parcelcopter 4.0. It is the new product resulting from the shared project "Deliver Future" between DHL and Wingcopter. The main purpose of the project is to deliver medical supplies to locations that are not easily reachable and those places that have challenging conditions for traditional transportation ways. [24] The drone was tested over a six-month period to fly to the isolated island called "Ukerewe" located in the middle of Lake Victoria, about 60 km far from the central warehouse in the city of Mwanza in Tanzania. [41]

According to [24] and [41], the drone specifications are the following:

- **Application:** Delivery of medicines, vital health supplies, and diagnosis results.
- **Aircraft type:** Tiltrotor, helps for vertical take-off and landing.
- **Payload:** Up to 4 kg.
- **Speed:** Up to 130 km/h.
- **Range:** Covers up to 65 km in approximately 40 minutes.

- **Delivery method:** Loading/unloading is done manually by human operators.

To sum it up, check **Table 2.1** which provides a brief comparison of the above-mentioned commercial drones in terms of the characteristics that are of interest to the thesis's purpose. Note: The values provided represent the maximum ability in an ideal environment.

Requirements	Matternet M2 V7 Quadcopter	Wingcopter 198	Zipline drone	DHL Parcelcopters
Weight	9.5 kg	20 kg	10 kg	N/A
Payload	2 kg	6 kg (5 kg with Triple Drop	1.75 kg	4 kg
Software	Proprietary (modified ArduPilot)	N/A	Navigation system is proprietary (ZipNav)	N/A
Speed	10m/s	40m/s	35m/s	36m/s
Covered Range	20 Km	See **Figure ??**	160 km	65 km
Flight time	15-30 minutes depending on cargo and conditions	See **Figure ??**	Delivers a product 80 km away in about 30 minutes	40 minutes

Table 2.1: Comparison of Commercial Drones

2.3 DIY Drones

Do-It-Yourself drones usually exist as kits ready for flight or to be assembled by the users/developers who want to build and program their own drones by putting all necessary components together.

Speaking about the advantages compared to commercial drones, customization is on top of the list as there are more options in the selection process of components, based on the goal and cost, to make it dedicated for the use case as much as possible, e.g., to focus on the payload capacity and ignore the speed. In addition, the used software is another point in DIY drones as developers are freely able to code the desired functionality using their preferred programming languages and platforms. [31] Examples for such kits are shown in **Figure 2.7**.

2.3.1 Robolink CoDrone Pro

This drone is considered to be the first one made for education purposes. It is programmable using Python or Blockly. Arduino can also be used to code its buildable remote controller. The kit includes all the essential components needed to assemble and program a full drone. As it is mainly suitable for young students to learn coding, some games could be played with it, e.g., do laser battles using the IR sensors. [38]

According to [38], the drone has the following specifications:

- **Weight:** 36g.
- **Signal type:** Bluetooth (other CoDrone types use radio).
- **Flight time:** 6-8 minutes.
- **Battery charge time:** Approx. 40 minutes.
- **Buildability:** Propellers, motors, and guards are replaceable and the remote controller is fully buildable.

2.3.2 Ryze Tello EDU Drone

The "Tello EDU" UAV is a programmable drone for the education purpose that can be coded in different programming languages such as Scratch, Python, and Swift. These are suitable for beginners but if it is needed to have more precise or complex commands, the tello SDK is improved for that case. The Tello EDU is using the DJI flight control system. [39]

According to [39], the drone has the following specifications:

- **Weight:** 87g (including propellers and battery).
- **Flight time/Range:** 13 minutes with a max of 100m distance.

- **Speed:** Max 8m/s.
- **Built-in functions:** Range finder, Vision system, 720p Live View (photo quality is 5MP).

2.3.3 DJI Matrice 600

This M600 is a hexacopter drone designed mainly for professional photographic aerial shootings. Its module is designed in a way that makes it easy and quick to be set up. The system is based on DJI A3 flight controller and the Lightbridge 2 for live HD videos transmission. From the programmability side, there are 2 SDKs, either Mobile App SDK or Onboard SDK can be used to make customized applications suitable to the intended purpose. In addition, Due to its ability to carry heavy weights (up to 6 kg), a variety of camera set-ups can be mounted to the drone. [35][12]

According to [35] and [12], the drone has the following specifications:

- **Weight (with six TB48S batteries):** 9.6 kg.
- **Payload:** Max 6 kg.
- **Flight time/Range:** 35 minutes without payload and 16 min with 6 kg payload for up to 5 km distance.
- **Speed:** Max 18m/s (no wind).
- **Built-in functions:** Range finder, Vision system, 720p Live View (photo quality is 5MP).

2.3.4 Pluto X kit

This product is more general than many other drones. Pluto X is considered an "Aerial Robotics Kit" that is mainly designed to be a quadcopter but can still be of another type, e.g., a rover. It is fully programmable and not designed for a specific purpose. The Pluto X board can be configured and programmed using the Cygnus IDE with C++ based APIs. It is also compatible with block programming using PlutoBlocks. [45][2]

According to [45] and [2], the drone has the following specifications:

- **Weight:** 60 grams.
- **Payload:** 15 grams.
- **Flight time/Range:** Around 10 minutes covering a distance of 70 to 100m.
- **SDK:** API based interface.
- **Additional Features:** It is crash-resistant and camera compatible.
- **Communication signal:** WiFi (60m).

2.3.5 Holybro Kit X500 V2

The X500 V2 kit is made for professional development with the Pixhawk-6C Flight Controller (supported by both PX4 and Ardupilot software stacks). It has a carbon fiber frame to be robust and light-weight at the same time. Furthermore, the big advantage of the kit is that it is designed in a way to be easily and quickly assembled in a short time (less than an hour). Also, it does not need soldering as some parts are already pre-installed and there are mounting holes for attaching other components/sensors, e.g., companion computers. [25]

According to [25], the drone has the following specifications:

- **Weight:** 610g.
- **Payload:** around 1 kg.
- **Flight time:** 18 minutes without payload.
- **Software:** Supported by both open-source autopilots PX4 and Ardupilot.

Moreover, There are other older Kits from Holybro (S500 and QAV250 Basic Kit) that are similar to the X500 but with some slight differences, e.g., in dimensions and weight. However, the core features and software/hardware supported are the same.

2.3.6 NXP HoverGames KIT-HGDRONEK66

This kit is a flexible DIY professional development module that is based on the NXP technology RDDRONE-FMUK66 flight management unit (FMU) which acts as the brain of the kit. The quadcopter drone kit is made of a full carbon fiber frame but needs assembly. It has no software on it but the controller board is supported by the PX4 flight stack software and could also be configured with other open-source stacks. Moreover, the NXP kit provides the needed mechanical and electronic components that comply with its FMU to make the drone ready for full operation (some items are not included and must be purchased separately due to shipping regulations). After the assembly, there would be enough additional room for mounting extra components or sensors for more accurate/advanced control of the drone. [16]

According to [16] and [34], the drone has the following specifications:

- **Weight:** 475g (without electronics and motors).
- **Frame size:** 500 mm diagonal and 200 mm height.
- **Payload and Flight time:** Can not be officially determined "as it is not a product, but rather a reference or evaluation tool" (quoted from [34]). But practically, it is recommended to be around 500g and a max of 1 kg depending on various factors such as motors, propellers, and battery capacity.
- **Software:**
    1. No software is provided by NXP itself. Supported by the open-source flight stack PX4.
    2. Includes supported connection for Rapid IoT with an add-on adapter board.

(a) Robolink CoDrone Pro [38]

(b) Ryze Tello EDU [39]

(c) DJI Matrice 600 [12]

(d) Pluto X Kit [2]

(e) Holybro X500 V2 [25]

(f) NXP Hovergames Kit [11]

Figure 2.7: DIY Drone Kits examples

3 Requirements

For achieving the intended goal to develop a functioning delivery drone, design specifications, hardware components, and software modules have to be compatible for building such an UAV. A programmable drone's FMU is necessary to code the exact customized functions and commands to the drone system. In operations dealing with heavy computational tasks, a reliable companion computer such as a Raspberry Pi is additionally needed for full and broader control of the drone. Moreover, the electronic and mechanical components selected must be able to function together in a way, that they can bear the parcel (payload) to be delivered.

Generally, the airframe must be stable enough and suitable for the type of payload. The max weight supported also depends on many factors, the motors' power capability for lifting the parcel load plus the drone's weight itself and the battery responsible for providing these motors with enough electric power to function at a maximum level. So, it is important to be aware that other components attached to the drone for any specific purpose, e.g., camera, will impact negatively as it would consume additional power and add up to the take-off weight. To sum this up, a proper estimation for the targeted weight of parcels is necessary and to also know that all of that is a trade-off for the flight time and covered range because the less weight attached to the drone, the more time/range the drone would last as the battery's discharge rate is less in that case.

Furthermore, there is a number of restrictions depending on the operation's location. In this thesis, Germany is the place of interest.

3.1 Germany's Regulations

Flying drones in Germany is put under 3 categories: Open, specific, and certified. Within the scope of this thesis, the "Open" category is considered as the other 2 categories are meant for special applications not needed here. In this category, permission is required from the relevant state's aviation authority if a special demand is needed, e.g., flying at night. So, apart from specific demands, flying a drone is approved if the following conditions are fulfilled: [20]

- **Minimum age of 16 years old.**
- **Maximum altitude above sea level is 120m.**
- **Maximum take-off weight of less than 25 kg.**
- **Drones must always be in a range where it is visible and in contact with the pilot.**
- **Insurance for drone liability is required.**
- **No flights over people.**
- **Operation is only during daylight.**
- **No transport of dangerous goods.**
- **No drop of items.**

In the "Open" category, there are more details in its three subcategories (A1 to A3) depending on different characteristics of the drone, e.g., weight. Firstly, for owning drones over 250g or having camera attached or sensors able to collect personal data, a drone operator registration is required. In addition, a competency certificate for the remote pilot is needed for flying a drone based on which category it belongs to. This is to prove that the pilot has the necessary knowledge and awareness before operating an UAV. [28] See **Figure 3.1** summarizing the requirements for these three sub-categories.

3.2 Project Requirements

In the following, the specific requirements relevant to the thesis's goal are analyzed and prioritized according to the level of importance.

Sub-category	Class	MTOM	Restrictions	Qualifications
A1	C0 or privately built	< 250 g	• No overflying of assemblies of people • Overflying of uninvolved persons permitted	None
	C1	< 900 g	• No overflying of assemblies of people • No overflying of uninvolved persons	EU certificate of competency
A2	C2	< 4 kg	• No overflying of assemblies of people • No overflying of uninvolved persons	EU remote pilot certificate
A3	C3, C4 or privately built	< 25 kg	• Minimum distance of 150 m from residential, commercial, industrial or recreational areas • Risks to uninvolved persons must be ruled out	EU certificate of competency

Figure 3.1: Overview of the "Open" category's three sub-categories. [27]

3.2.1 Weight

As discussed in the previous section about the allowed weight related to each required license, the drone mass including payload must be less than 25 kg. And to avoid additional authority approval, the preferable maximum take-off mass (MTOM) is to be below 900g. Otherwise, "a minimum distance of 150 m from residential, commercial, industrial or recreational areas" must be ensured. [27] Apart from the country's regulations, it is better to target lighter drones that still have a reasonable carrying ability.

3.2.2 Payload

This is one of the most important requirements for the thesis's goal. It is preferred to have a drone that can carry as much payload as possible but at the same time, the drone's performance does not get affected negatively because of it. This means, after knowing the maximum load supported by the system, it is expected to operate with less payload to sustain the other aspects of the flight such as speed, flight time, and energy consumed. Hence, a minimum of 300g is reasonable for this prototype.

3.2.3 Software Supported

The software to be used is a fixed requirement from the stakeholder. It is requested to develop a drone based on the PX4 flight stack software.

3.2.4 Cost

The total cost of the components must be not higher than the project's budget of 1.500€.

3.2.5 Flight Time/Speed

Generally, the longer time the drone can last during a single operation, the better. The same applies to the speed, the more maximum speed attainable, the better. However, these two factors are not of much interest for this particular goal as long as they are enough to achieve the delivery operation, which is the general feasibility of a small-size drone. Another reason as discussed earlier, these requirements vary and depend on many factors, e.g., payload attached, weather circumstances, motors' capability, and battery capacity. Hence, a minimum goal is set. A minimum speed of 5m/s and 5 minutes of flight time are decided.

3.2.6 Community Support

Community support is also an important aspect when it comes to dealing with new technologies. There must be documentation containing helpful information for the development process such as assembly instructions and a detailed explanation about the components included, the software supported, and how to put them in use.

3.2.7 Availability

As for the current situation, there is a global shortage of hardware chips and it is not unexpected if delivery of such chips and electronic components is taking a long time. Therefore, availability must be taken into consideration. A suitable delivery time must not exceed 2 weeks due to the thesis's allocated time. Because this factor is changing constantly according to the market stock, it is to be evaluated shortly before the purchase date.

3.3 Prioritization

In order to reach a clear and justified decision, only comparing the requirements for the potential solutions is not sufficient to have a conclusion for the proper system because not all aspects have the same importance. That is why a classification of these points is needed and there are many approaches to do so. Here, the prioritization is based on a weighted score. The weights for the requirements range from 1 to 3 (1 is the lowest and 3 is the highest) and have a corresponding rating from 1 to 3.

For rating each requirement, the minimum (Rate 1) and maximum (Rate 3) limits are set. The limits for the numbers between that range are estimated accordingly.

- **Weight:** Rate 1 corresponds to the heaviest weight and its limit starts from 2 kg. Rate 3 corresponds to the lightest and is defined for drones up to 500g. This requirement is assessed to have an intermediate level of importance, hence a weight of 2 is given.
- **Payload:** Rate 1 corresponds to the minimum payload bearable and is defined for a range from 300g to 500g. Rate 3 is defined for payloads from 2 kg. This requirement is assessed to have a high priority, hence a weight of 3 is given.
- **Software Supported:** As this is a hard requirement, it is either met or not (PX4 Software).
- **Cost:** Rate 1 corresponds to the most expensive drone and is defined for drones starting from 1000€ to 1500€. Rate 3 corresponds to the cheapest and is defined for up to 500€. This requirement is considered a low priority, hence a weight of 1 is given.
- **Flight Time:** Rate 1 corresponds to the shortest flight time attainable and is defined for a range from 5 minutes to 7 minutes. Rate 3 is defined for a flight time from 9 minutes. This requirement is considered a low priority, hence a weight of 1 is given.

- **Flight Speed:** Rate 1 corresponds to the least max. speed attainable and is defined for a range from 5 m/s to 10 m/s. Rate 3 is defined for a speed from 14 m/s. This requirement is considered a low priority, hence a weight of 1 is given.
- **Community Support:** It has no ratings. The requirement is either met or not.
- **Availability:** Rate 1 corresponds to the latest delivery time and is defined for times starting from 10 days. Rate 3 corresponds to the earliest possible delivery date and is defined for times up to 4 days. This requirement is critical and is of high importance, hence a weight of 3 is given.

4 Conception

4.1 Hardware Solution

In the following, alternative solutions are compared based on the requirements.

4.1.1 Comparison

Firstly, commercial drones are excluded as they are designed for a specific purpose and are not freely programmable. Also, their expenses exceed the cost limit required. From the "DIY drones" section, the UAVs robolink CoDrone, Ryze Tello, and Pluto X are excluded due to a critical reason that they are tiny and light drones (less than 100g) with the inability to carry considerable payloads (max. 15-20g). Some of them even miss the information about the payload capability and would need to be tested first. Thus, three drone kits are left to compare their specifications against the defined requirements.

Requirement	DJI Matrice 600	Holybro X500 V2	NXP HoverGame
Weight	9.6 kg	610g	475g
Payload	6 kg	1 kg	500g to max 1kg
Software	DJI Assistant 2	PX4 and ArduPilot	PX4
Cost (approx.)	6,000€	1100€	600€
Flight Time	16 minutes (with payload)	N/A	N/A
Flight Speed	18m/s	N/A	N/A
Community Support	No	Yes	Yes
Availability	Unknown	within 2 days	within 2 days

Table 4.1: Comparison of Potential Kits

4.1.2 Decision Making

Following the comparison in **Table 4.1**, a detailed evaluation is carried out based on the prioritization and ratings set in the requirements analysis chapter.

Rating	DJI Matrice 600	Holybro X500 V2	NXP HoverGames
Weight (2)	1	2	3
Payload (3)	3	2	2
Software (Req. met or not)	Not met	met	met
Cost (1)	Exceeds limit Req. not met	2	3
Flight Time (1)	3	N/D	N/D
Flight Speed (1)	3	N/D	N/D
Community Support	No	Yes	Yes
Availability (3)	3	3	3
Total points	**Excluded due to not-met Requirements**	**21**	**24**

Table 4.2: Evaluation of the Potential Kits' Comparison

After the analysis in **Table 4.2**, the DJI Matrice 600 is out of the competition due to the unfulfilled requirements of the software, cost, and community support. Comparing further between the HoverGames and Holybro kits, the decision goes with the NXP HoverGames kit based on the adopted analysis approach (weighted score). However, it is found that their characteristics are noticeably close to each other with minor differences as the following:

- **Weight**: The NXP Hovergames drone is lighter.
- **Cost**: The NXP Hovergames kit costs less.
- **Flight time**: Although the flight time is not precisely mentioned in NXP drone details, it does not impact the goal as long as it satisfies the minimum requirement which is the case.

- **Estimated assembly time**: Although the estimated assembly time for the Holybro kit is much shorter, this is not a significant factor for the objective.

4.1.3 Decision Validation

Further analysis of the drone design is done to make sure it complies with the regulations, requirements, and the goal of delivery operation.

- **Material**: The NXP Hovergames kit's frame is made of carbon fiber which is known for its high strength and rigidity compared to other strong materials, e.g., steel. At the same time, it has a much lighter weight [3]. For such facts, carbon fiber has the best combination suitable for this thesis' purpose as stiffness and lightness are desired to be more resistant to crashes and save as much weight for the payload as possible rather than for the drone's weight itself.
- **Mount/Payload space**: The kit design provides extra room for mounting other components/items, e.g., sensors, cameras, and payloads. This serves the current goal of delivery or even for future improvements using extra sensors or a companion computer. [11]
- **Community support**: Hovergames community support provides helpful information about different aspects of drone development, from assembly to troubleshooting. It has also advice and tips for optimal performance based on previous trials and experiences. They provide a forum as well to ask about specific problems that other members, including experts, can answer and help with. [34][6]
- **Warranty request**: NXP provides the warranty request service. It eases the development process in case there are defective or missing parts delivered and these are to be replaced upon request.

For drone stabilization, a flight attitude control system needs to be integrated into the controller software. This system is based on Inertial Measurement Units (IMUs) consisting of a combination of different motion sensors such as an accelerometer, Gyrometer, Magnetometer, and Barometer. The measurements from these sensors are core data for the flight controller to produce the correct signals for controlling the motors. Inaccuracy of these data would cause a crash in most cases. [42]

Based on that, this drone is a proper choice as the core of the kit is its FMU "RDDRONE-FMUK66". It is an NXP technology designed as a basis for the development of robotic vehicles such as rovers, drones, and even water-based systems. [33] It includes the essential sensors needed for providing the drone kit with the capability of operating delivery missions within the scope of this thesis. These sensors are:

- **3D Accelerometer + 3D Magnetometer (FXOS8700CQ):** The accelerometer senses the linear motion/acceleration along the 3 axes. So, it detects, e.g., the up/down and left/right movements. The magnetometer senses the strength and direction of the earth's magnetic fields to determine precise headings along with the other sensors and GNSS. [19]
- **3D Gyrometer (FXAS21002C):** It senses the angular motion around the 3 axes. So, it detects changes in the orientations and rotations of the drone, namely, the angles of pitch, roll, and yaw movements. [19]
- **Barometer (MPL3115A2):** It helps by sensing the altitude position.

Check the FMU block diagram in **Figure 4.1** for more details about the modules integrated into the FMU.

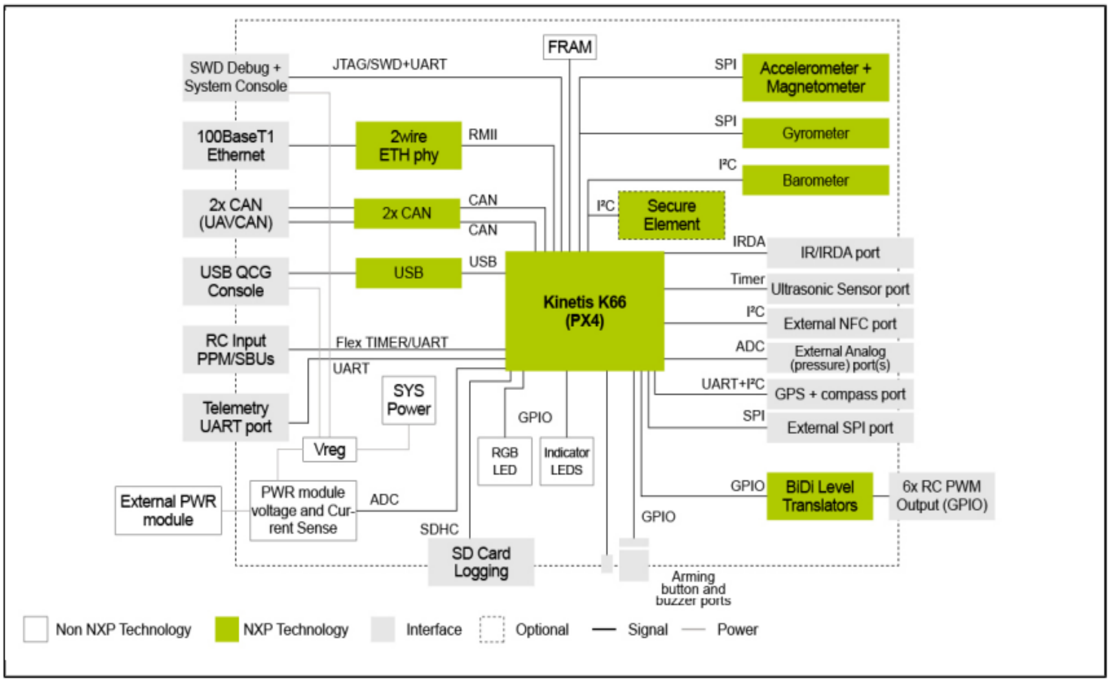

Figure 4.1: HoverGames drone kit Block Diagram. [33]

4.2 Software Solution

4.2.1 Possible Approaches

From the software side, this RDDRONE-FMUK66 design supports open-source flight stacks including PX4, the standard for industrial drones. It has flexibility for developing own robotic vehicles. [33] With PX4, the supporting SDKs, and ground stations, different approaches can be implemented to achieve the goal.

- **Mission planning:** Using ground station applications, e.g., QGroundControl, a customized autonomous mission with predefined route GPS waypoints can be determined on the map. Also, other parameters such as the desired altitude and flight speed can be adjusted. After finishing the plan details, the mission can be uploaded to the flight controller. The view of such a plan looks similar to the view in **Figure 4.2**

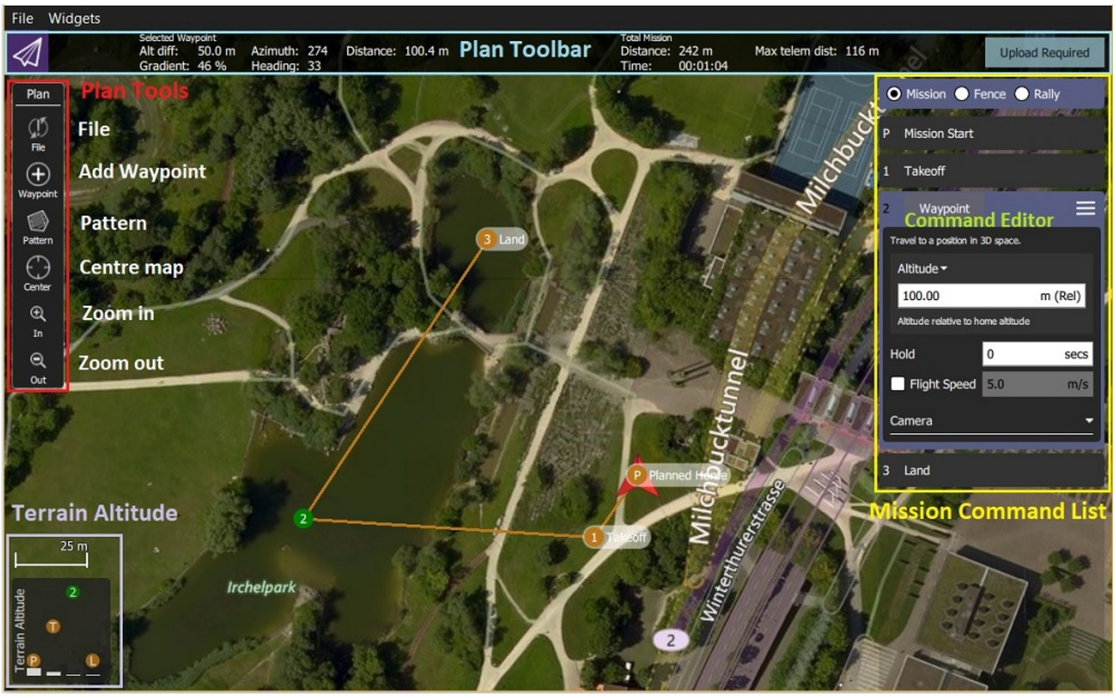

Figure 4.2: QGroundControl mission planning view. [14]

- **Offboard Mode:** Among different possible flight modes in PX4, the drone can be controlled relative to the current position and direction in the offboard mode. This mode can be operated without GPS and it controls the drone by sending direct MAVLink commands to the flight controller. The control approaches are either using the position or velocity NED (north, east, down) coordinates.

4.2.2 Payload loading/unloading mechanisms

For delivery drones, a couple of techniques can be adopted to serve the purpose of holding the items and delivering them when the drone arrives at its destination.

- **Automated design**: Servo motors can be included in the drone and programmed to control, for example, a gripper for picking up items and then release it to drop the item at the specified location.
- **Manual design**: In this technique, the drone just needs to have a suitable space for the items to be delivered. Then human operators load and secure the package and take the item from the drone.

4.2.3 Adopted Approach

The better approach is to use the mission mode as following the GPS coordinates has more accuracy than the offboard control in determining the exact destination location. However, Due to the stakeholder rules that the drone operation must be done in-house, the offboard mode solution is chosen for this task as the GPS signals are not reliable indoors.

Moreover, the manual approach for mounting the payload is preferred because of its simplicity. For the thesis's limited time, the priority is to save effort and time for the software implementation as it is enough to prove the concept.

5 Development

5.1 System Components

A detailed check of the components included in the kit is carried out before the purchase process to decide whether further necessary items are to be purchased separately. The kit block diagram in **Figure 5.1** illustrates more about the included, not included, and optional components/modules.

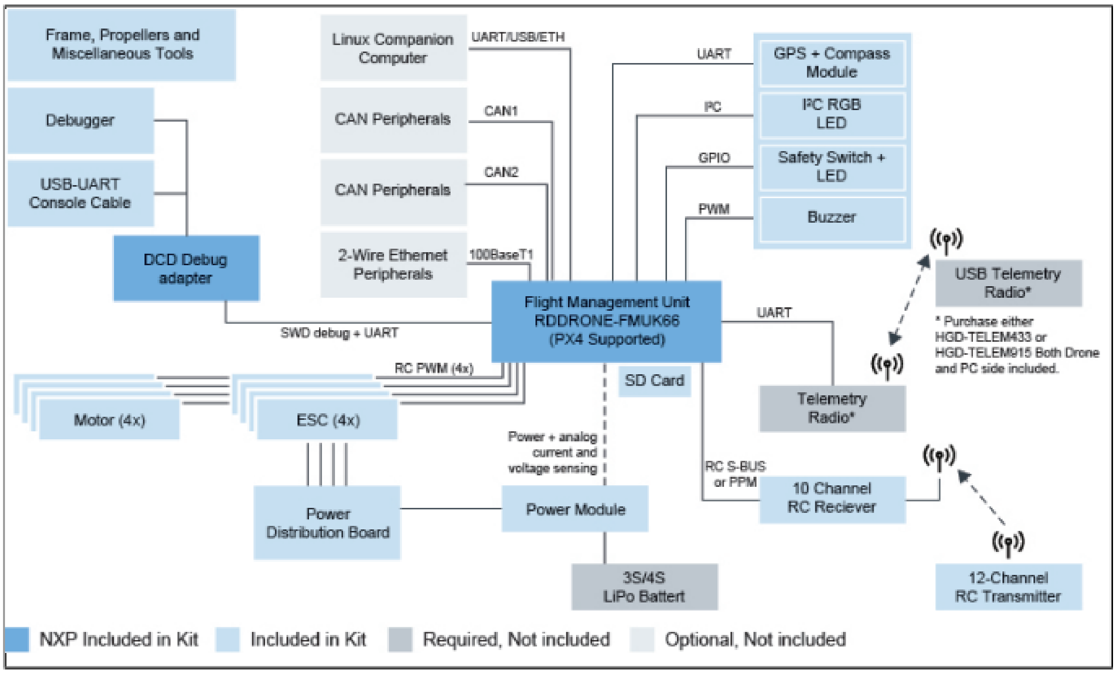

Figure 5.1: HoverGames drone kit Block Diagram. [32]

5.1.1 Included items

The following components are included in the kit package:

- **Frame (carbon fiber)**
- **Propellers**
- **FMU "RDDRONE-FMUK66"**
- **4 Motors**
- **4 ESCs**
- **RC Transceivers**
- **Power Distribution Board**
- **Miscellanous cables, screws, and tools**

5.1.2 Required but not included items

The following components are not included in the kit but are necessary to have a complete functioning UAV. Thus, they are bought separately:

- **LiPo battery and charger**
- **EU telemetry radio**

5.1.3 Optional and not included items

There are optional components that can be helpful for delivery drones but will not be considered in this project:

- **Distance/Optical Sensors** In most cases, distance sensors such as cameras and LiDARs are crucial for drones for safety purposes, e.g., collision avoidance. However, this would need extra effort out of the thesis's scope. So, the drone is operated without such sensors but a safe flying environment is to be ensured.
- **Companion Computer:** In use cases where heavy computational tasks are involved, e.g., computer vision and other machine learning approaches, a companion computer such as Raspberry Pi is needed in addition to the flight controller which has limited resources for such intensive processes. [10] Nevertheless, for the planned prototypical task, the FMU alone is capable enough for the goal.

5.2 Assembly

Having the necessary mechanical and electrical components ready, the assembly process is done by connecting the kit parts along with the frame as instructed to have a stable and robust design. Following the kit instructions carefully and in detail should satisfy that purpose and prevent potential inconvenience during and after the assembly process.

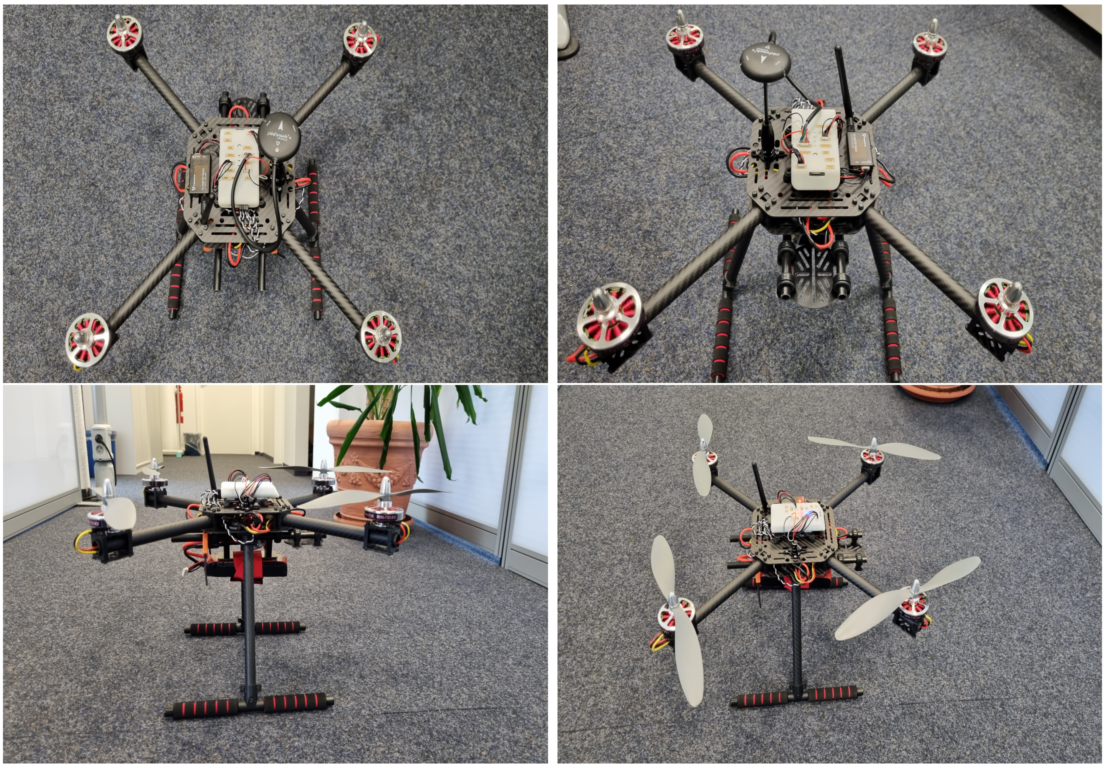

Figure 5.2: Assembled Hovergames Drone kit

5.3 Environment Setup

As a start into the software setup, a Developer Environment (tool chain) is set up first. The best-tested supported environment for PX4 is Ubuntu. As windows is the available operating system, an Ubuntu virtual machine is used.

Next, the PX4 software source code is fetched from GitHub which also includes a bash script for installing the needed tools to build PX4 for different simulated and hardware targets. In addition, the bootloader needs to be written to the RDDRONE-FMUK66 using a debugger board (included in the kit) and then the PX4 firmware is flashed using either the same debugger board or the QGroundControl application.

5.3.1 Brief Background

The flight stack and programs used in this project are explained briefly to have a better understanding of how they function and why they are needed.

- **PX4 flight stack:** PX4 software is supported by various hardware references, e.g., Pixhawk. The PX4 code is built on a Real-Time Operating System (RTOS) named Nuttx. [7]

  The PX4 flight stack consists of a number of essential components controlling different vehicle types and airframes, e.g., fixed-wing and multi-copter. **Figure 5.3** gives an overview of the building components of the flight stack.

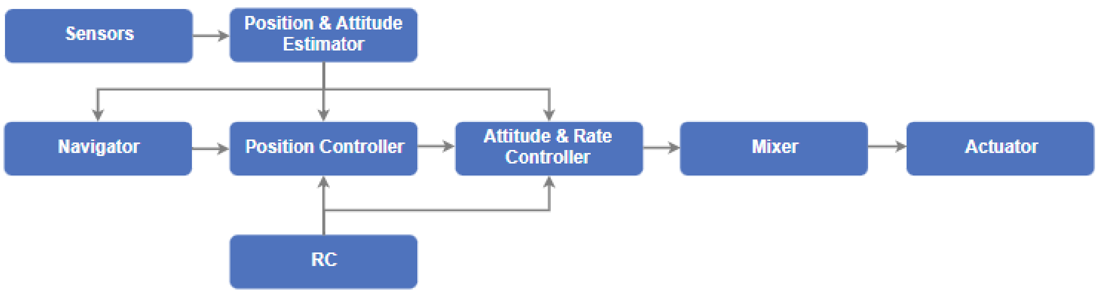

Figure 5.3: PX4 Flight Stack Components. [7]

- **QGroundControl:** This is the ground control station designed by the Dronecode foundation. QGroundControl comes with many use cases such as flashing the firmware onto the vehicle control hardware, setting up the vehicle, changing different parameters, calibrating drone and RC radio switches/buttons, getting real-time flight information, and planning and executing autonomous missions. [8]

- **MAVSDK:** It is a library with a collection of APIs allowing communication to the drone through the MAVLink protocol using common programming languages, e.g., Python and C++. The SDK architecture, how the communication occurs, and using Python for coding the drone are demonstrated in **Figure 5.4**

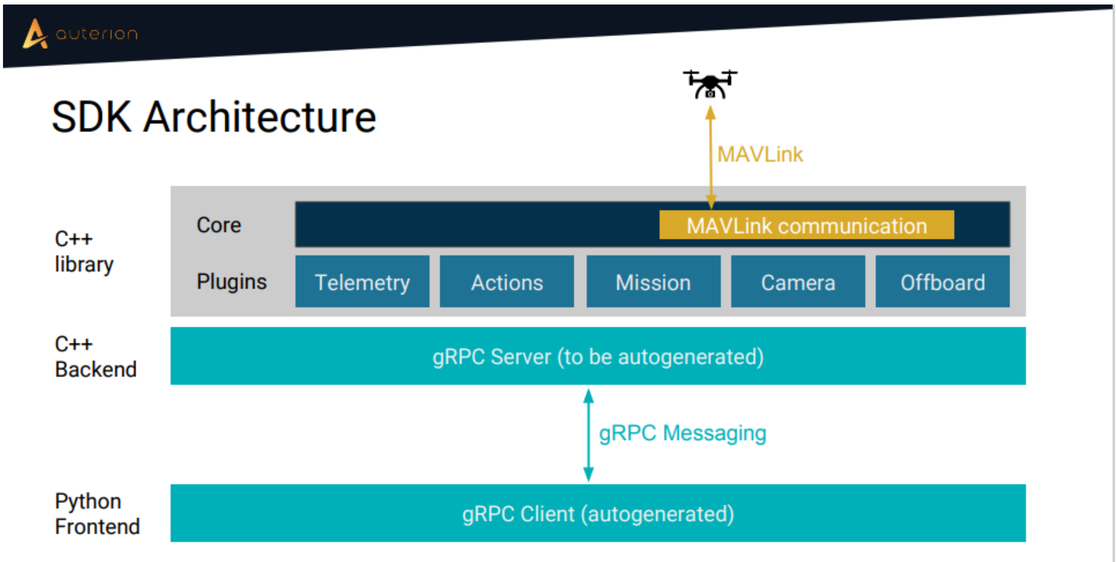

Figure 5.4: SDK Architecture. [30]

5.4 UAV Setup

When the bootloader and firmware have been flashed to the flight controller, the drone gets automatically detected by the ground station "QGroundControl". There are some parameters adjusted and configured there for optimal performance.

- **Airframe:** The customized airframe called "NXP Hovergames" is selected from the list of Quadcopter frames.
- **Sensors calibration:** For first use, the controller sensors are calibrated to suit the surrounding environment best.
- **Radio controller:** RC buttons and switches are synchronized with the FMU by following the instructions in QGC.
- **Power and ESCs calibration:** The battery parameters, e.g., number of cells and voltage values are set according to the purchased LiPo battery details. Also, the ESCs need power calibration for first use.
- **Software parameters:** There are software parameters to be controlled based on the desired mission and behavior. For example, there is a parameter that enables arming the drone without a GPS lock detected, which is useful for the adopted approach when flying indoors where poor GPS signals persist.

- **Motors Testing:** The power and functionality of the motors are checked and tested from the sliders in the "motors" tab (propellers should be removed in this step for safety). In addition, the wiring order of the motors' drivers to the flight controller and the rotation direction of the motors are verified.

These configurations above are carried out through the QGC settings view as shown in **Figure 5.5**.

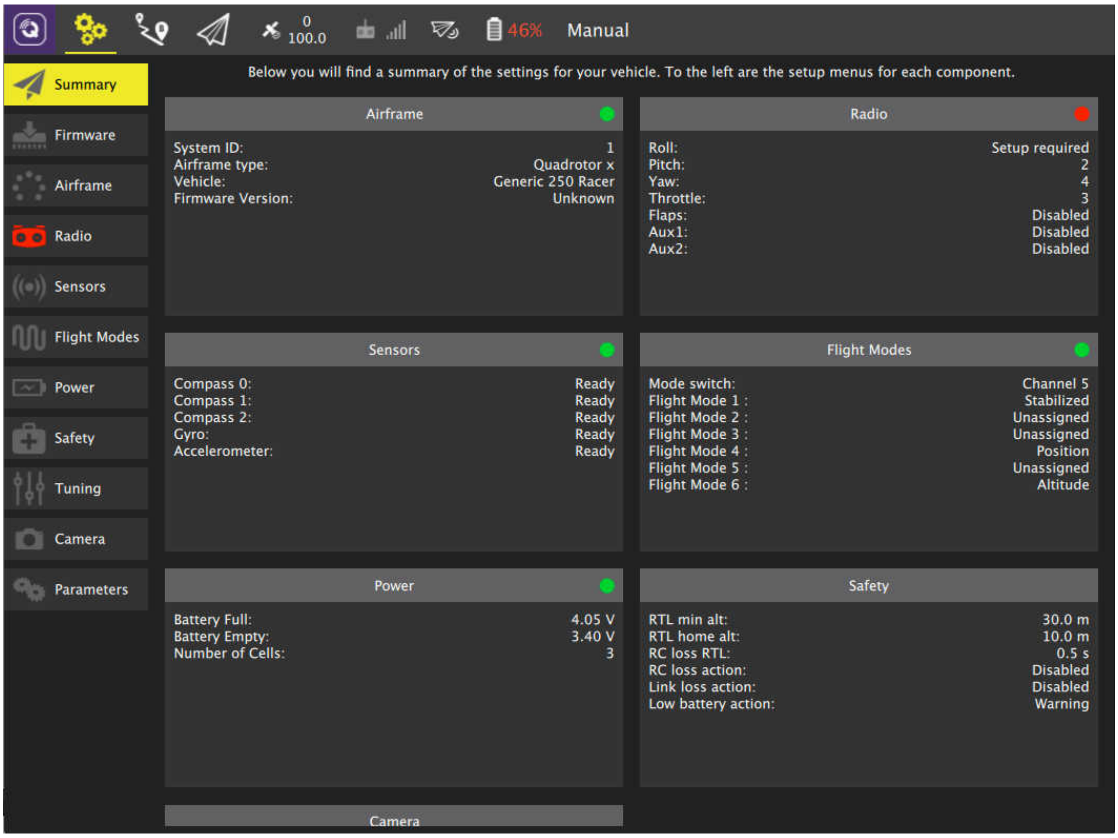

Figure 5.5: QGC Vehicle Setup View. [8]

5.5 Software Code

The MAVSDK Python API is used for programming the delivery mission logic. For reasons mentioned before, the functions from the offboard mode are utilized. In more detail, the velocity_NED approach is considered as it enables control of the drone speed for each movement. Whereas in the position_NED functions, only the distance is determined without controlling the speed, and this can affect the motion smoothness of the drone (stops immediately after a high speed, for example). The flowchart in **Figure 5.6** shows the delivery operation logic.

5.6 Encountered Issues

5.6.1 Defective Hardware

During testing the motors, it was noticed that a specific motor is not functioning stably and another motor has a relatively different speed. After trying different tests aiming to determine the core issue, a motor, and an ESC were found to be defective and got replaced.

5.6.2 Design Flaws

During the assembly process, there were stages where connecting parts was not convenient. For example, to connect the motors with their arms, the space was too limited to tighten the screws freely. In addition, some 3D-printed parts were not fixed enough to the frame or were not of the perfect size for the screws. These had to be replaced.

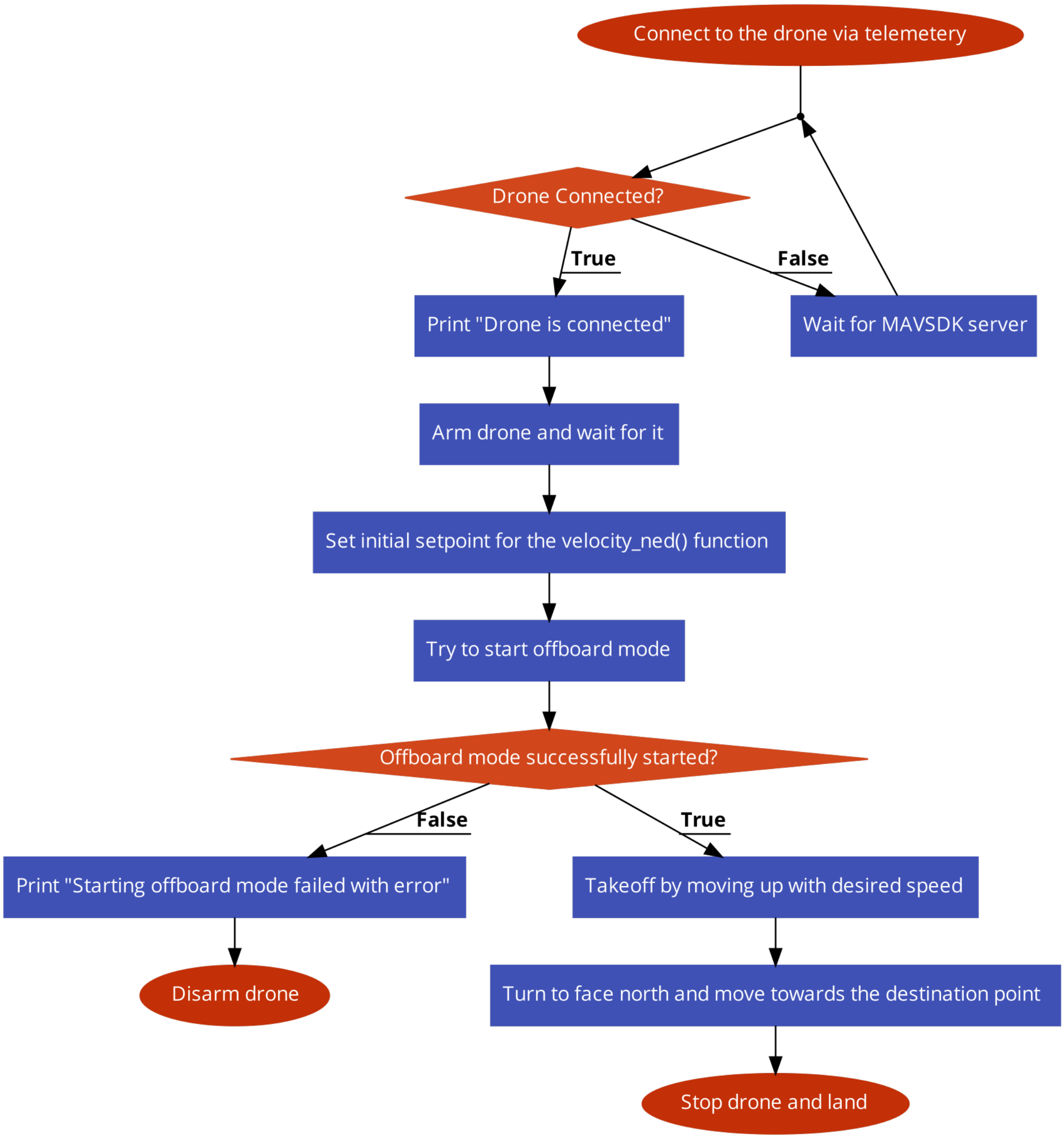

Figure 5.6: Flowchart of the Software Logic

6 Test and Validation

6.1 Resulting System

The final drone setup has the following details:

- **Total drone weight (including battery):** 1530g
- **Battery weight:** 274g
- **Airframe:** NXP HoverGames Quadrotor x
- **Hardware:** NXP_FMUK66_E
- **OS Version:** NuttX, v11.0.0

6.2 Experiment with Manual Control

Having the drone configured and set up, it is ready for the first flight attempt. For this, basic manual control of the drone via the RC is done to make sure the general behavior of the drone is as expected and that it reacts properly to the controller commands.

6.2.1 Experiment Outcome

The behavior was not as expected and the drone kept flipping over to different random directions on attempting to take off. In a better attempt, it could partially take off but with great instability and hit the wall.

6.2.2 Troubleshooting

The issue investigation approach was done aiming to determine the problem source whether it is hardware or software related. The process included double-checking the drone's wiring, testing motors' power, re-calibration, trying different software versions on the flight controller, etc. The main issue was contained and was related to the unbalanced speed of the four motors, specifically, the decision of the PWM values coming from the FMU itself. For example, the cause of flipping over forwards was due to the faster rotation of the two back motors compared to the other motors. Such behavior is not expected in a landing position.

These PWM_output values range nominally from 1000 to 2000. They represent the four motors' power and can be visually monitored in real-time through the MAVLink analysis tool in QGC as shown in **Figure 6.1**. NOTE: This image is captured in takeoff mode for a simulated vehicle. That is why the values are nearly ideal.

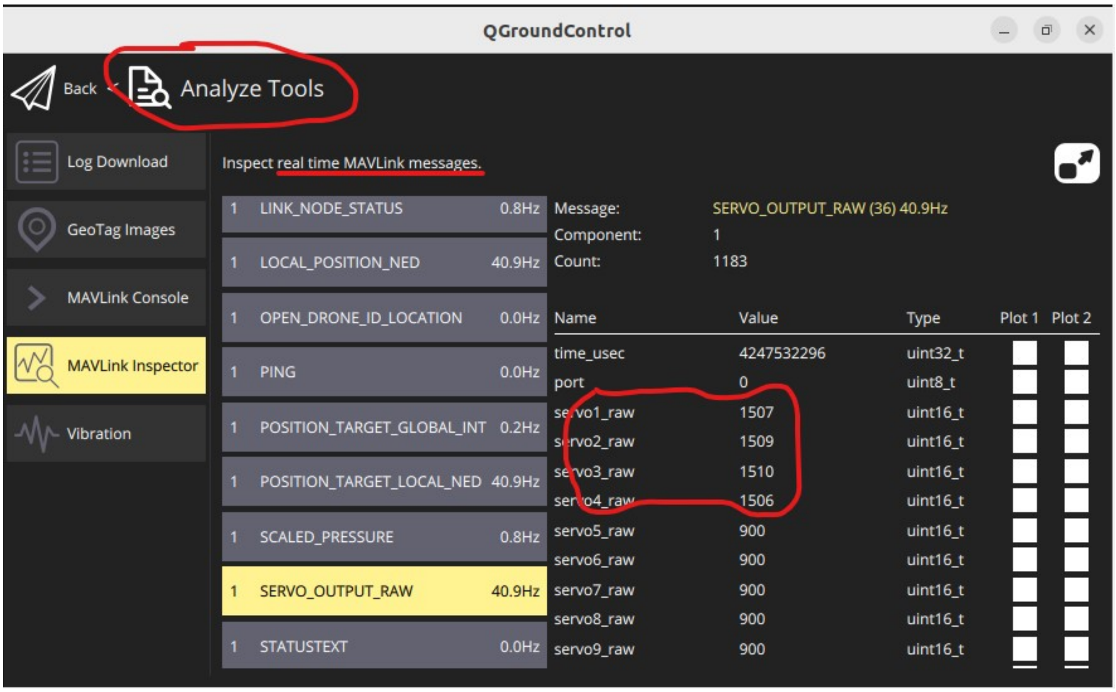

Figure 6.1: QGC MAVLink Inspector for Servo Values

Due to the fact that these PWM values are sent from the FMU to the ESCs based on the current drone's position and tilt, which are detected by the motion sensors embedded in the FMU, the solution direction was to make sure the sensors are as precise as possible by performing sensors re-calibration more accurately. This was also visually validated through the QGC analysis tool as shown in **Figure 6.2**. The pitch and roll values are the most important indicators to check the tilt readings. The ideal reading is zero when the drone is stable on the ground. It is advisable to re-calibrate the sensors if the pitch/roll values exceed +/- 0.02.

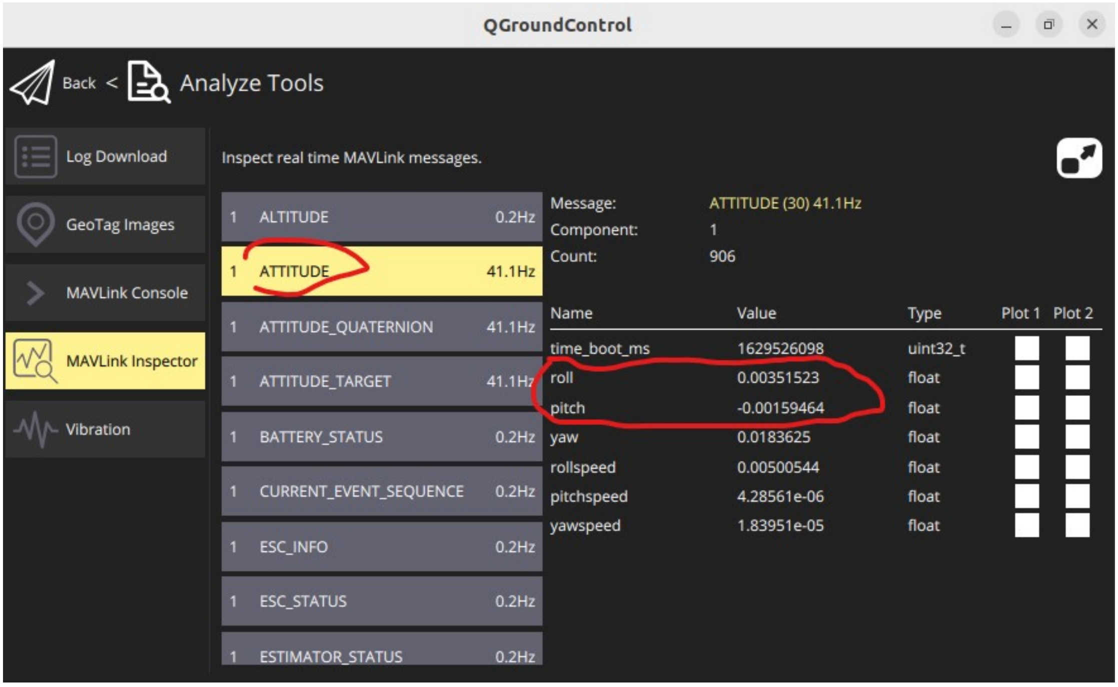

Figure 6.2: QGC MAVLink Inspector for Attitude readings

6.2.3 Behavior Improvement

There has been a noticeable improvement after applying the solution from the troubleshooting above. With the setup shown in **Figures 6.3, 6.4, and 6.5**, the drone was able to take-off upon increasing the throttle power above 50% but there was still a difficulty with hovering in place. Unexpectedly, the drone keeps flying slowly towards a random direction, getting closer to the room walls. So, an emergent landing is commanded before a crash happens.

6.3 Flight Analysis Tool

To have detailed information about operated flights, log files are saved to the SD card inserted in the FMU and can be downloaded to analyze the flight's behavior using different analysis programs such as the "Flight Review" tool. Through various graphs, this tool can demonstrate related information such as flight speed, flight duration, roll/pitch angles, and vibration rates. [1]

In **Figure 6.6**, the graph shows the frequency response of the raw accelerometer data over time. Typically in such a graph, colors range from yellow to blue shades with high-frequency responses and low-frequency responses, respectively. Ideally, at lower frequencies, it would be yellow but the rest would mostly differ from green to blue. Moreover, in **Figure 6.7**, The plot illustrates the raw acceleration values over time in the three axes. If the plots for the x/y-axis are well separated from the z-axis plot, it means the vibration levels are low which indicates good flight behavior.

Analyzing the current behavior, it is seen that the vibration rate is increasing by time, noticeably, upon takeoff after minute 3:36. At that time, there are sharper yellow areas in **Figure 6.6** and there is an overlapping of the x/y-axis plots with the z-axis plot in **Figure 6.7**. Both observations indicate high vibrations.

6.4 Possible Improvements

As the current behavior is not sufficient for carrying out a delivery operation, further analysis of the instability issue is performed. The following points contribute to the problem:

- **Vibration:** Vibrations impact the drone's stability and make its control harder. They are caused due to some factors, e.g., loose cables like the highlighted part in **Figure 6.3**. This needs to be secured to have the loose cables' length as short as possible. Also, all drone parts, e.g., landing gears need to be tightened firmly to prevent vibrations as much as possible.
- **Electromagnetic Interference (EMI):** EMI can affect the functionality of electric components or disturb the sensors, leading to reading errors, and hence, un-

expected behaviors could occur. To minimize the EMI effect, secured and shielded cabling as far as possible from EMI sources is recommended.

- **Ground Effect:** For better stability, the takeoff altitude needs to be approximately over 1 m to reduce the ground effect (An increase in air pressure under the drone which causes it to change the power thrust given). The higher the drone gets, the lower the ground effect is. [29]
- **GPS Mounting:** Even during indoor operations, mounting the GPS still helps as it has an additional magnetometer less disturbed by the magnetic field (of the ESCs) than the FMU onboard magnetometer.

The final drone setup is adjusted after considering the improvement points mentioned above. See **Figures 6.8 and 6.9**.

6.5 Code Testing and Result

The code is not fully tested due to the possible dangerous consequences of flying the drone in the available room. However, it is tested with the propellers removed to observe how the drone reacts to the code commands.

The code execution was successful as the motors' speeds were changing upon the code commands. This indicates the responsiveness and successful communication between the drone and the code. Theoretically, the software would work outdoors with better sensors functioning, especially with the GPS enabled, and a bigger space.

6.5.1 MAVLink Routing

To communicate with the drone through the MAVSDK API and to observe the behavior in QGroundControl simultaneously, MAVLink routing is used. This is because both MAVSDK API and QGC talk to the drone via the telemetry radio connected to a USB port. The MAVLink routing is used to forward the MAVLink messages from the telemetry USB port to two different UDP ports, one for MAVSDK and the other for QGC. The command used looks something like the following:

```
$ mavlink-routerd -e 192.168.7.1:14550 -e 127.0.0.1:14540 /ttyUSB0:57600
```

6.6 Requirements Fulfillment

1. **Weight:** From section 6.1, the total drone weight is below 25kg.
    - **Requirement is fulfilled**
2. **Payload:** Could not be well tested due to the drone's instability.
    - **Requirement is not tested**
3. **Software supported:** The software PX4 is run successfully on the board.
    - **Requirement is fulfilled**
4. **Cost: The components costed around 700€ which is below the budget limit.**
    - **Requirement is fulfilled**
5. **Flight Time:** Could not be well tested due to the drone's instability. However, it is shown in the performed flight analysis that the remaining flight time is above 1 hour, which exceeds the minimum required. [37]
    - **Requirement is theoretically fulfilled**
6. **Flight Speed:** Could not be well tested due to the drone's instability and insufficient flight time.
    - **Requirement is not tested**
7. **Community Support:** It exists and is confirmed that the information provided there is updated and applicable to the drone.
    - **Requirement is fulfilled**
8. **Availability:** Drone is delivered within 3 days.
    - **Requirement is fulfilled**

Figure 6.3: Initial Drone Setup

Figure 6.4: Initial Drone Setup

Figure 6.5: Initial Drone Setup

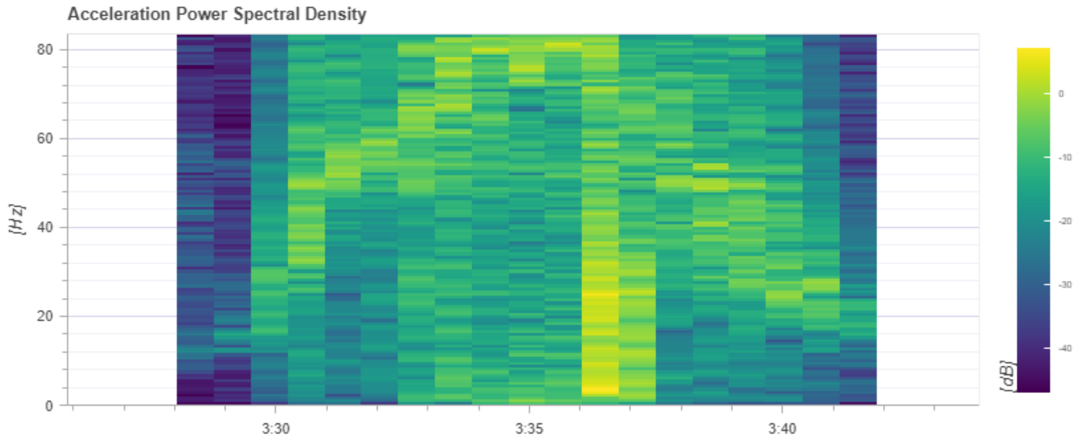

Figure 6.6: Acceleration Power Spectral Density

Figure 6.7: Raw Acceleration

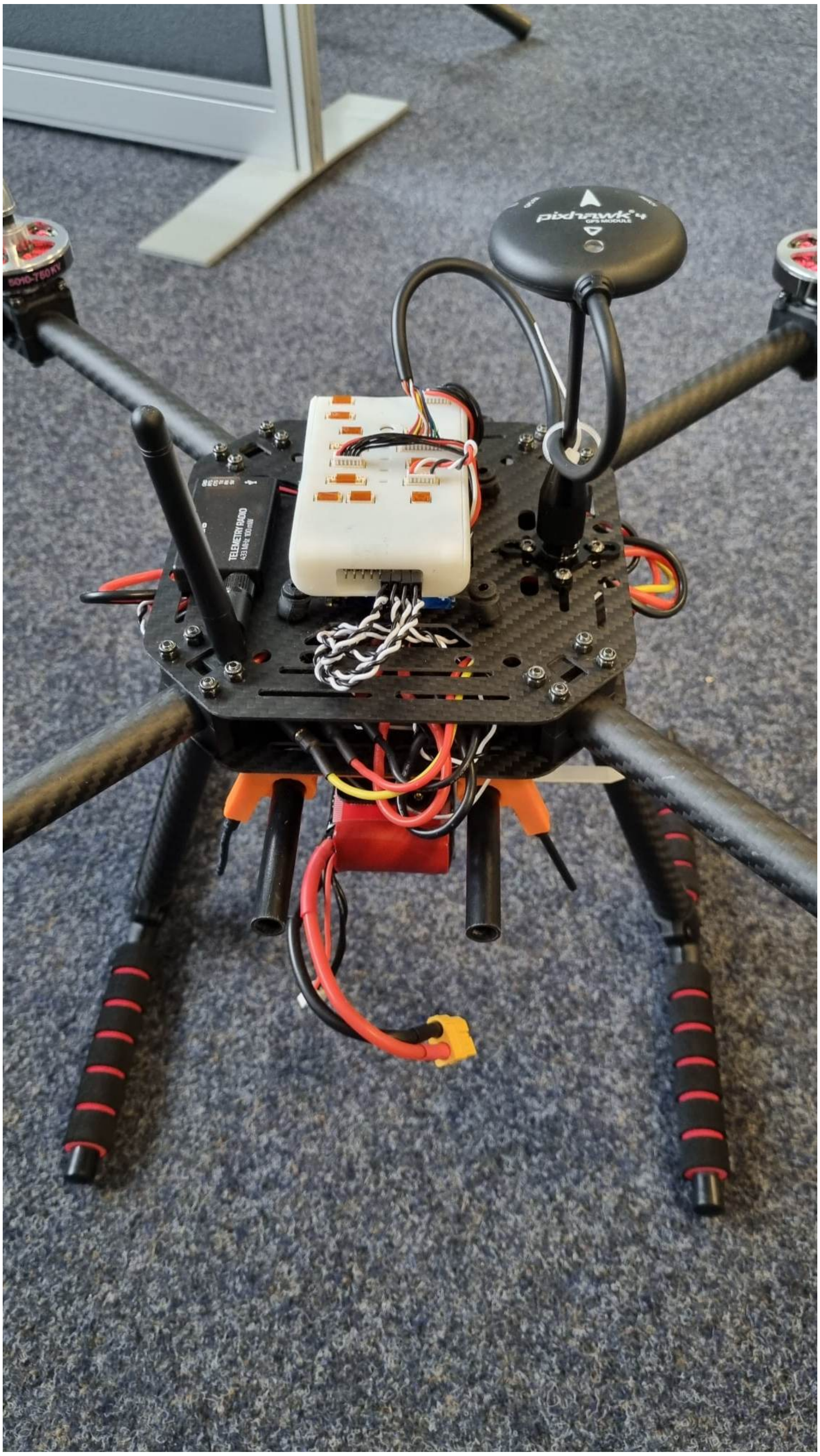

Figure 6.8: Final Drone Setup

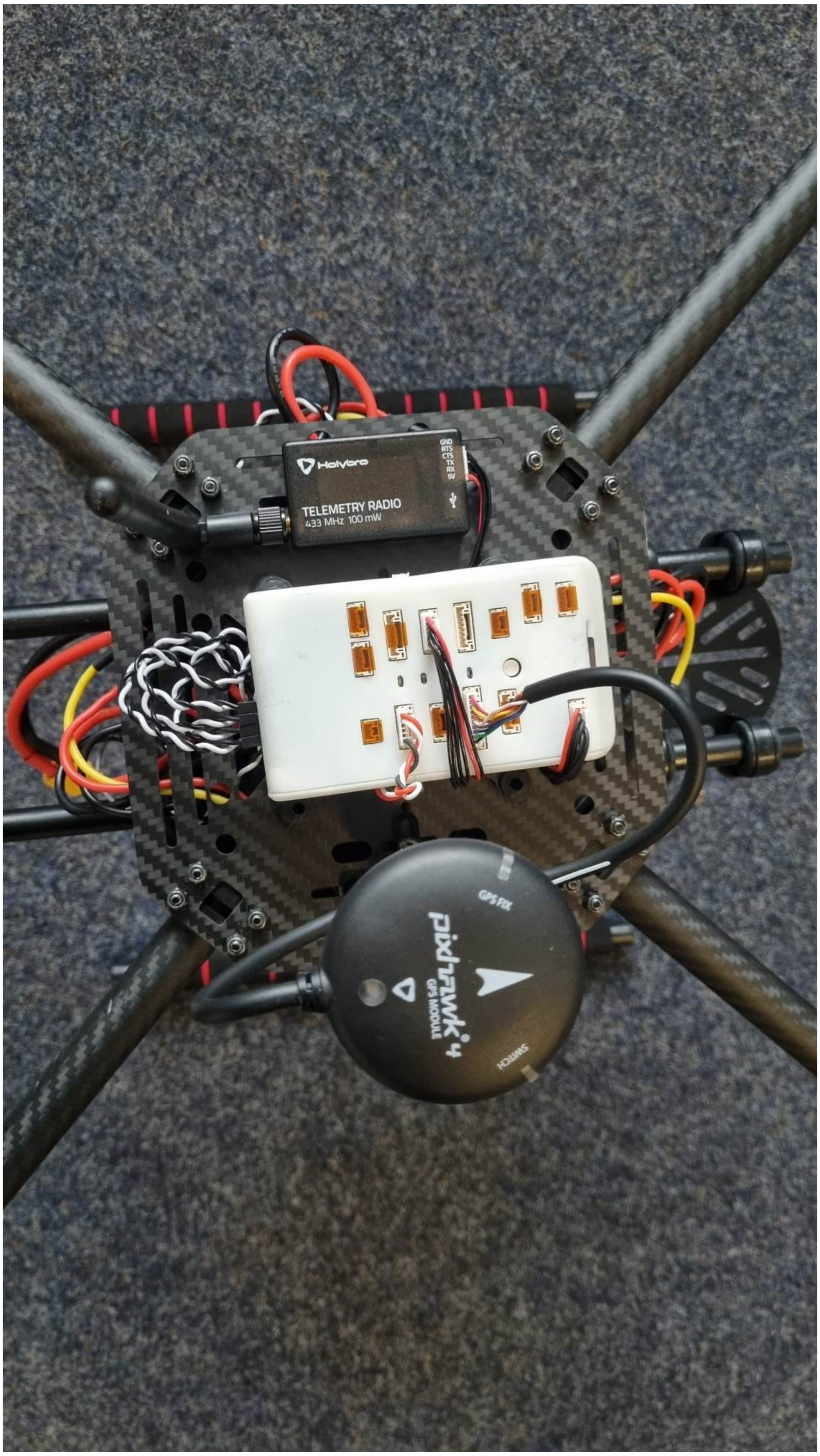

Figure 6.9: Final Drone Setup

7 Summary

This thesis aimed for a developed reliable UAV system capable of performing delivery tasks. The approach started by having a general overview of the drone technology and what types of drones exist in the market. Comprehensive literature was also part of identifying the possible technical operations of drones and an idea of the crucial requirements that delivery drones must meet.

In chapter 2, the basic concepts, UAV categorization, and drone working mechanism were discussed along with the needed components for designing an UAV. Also, examples of available commercial delivery drones and DIY drone kits were addressed briefly with their specifications.

In chapter 3, general requirements and characteristics of drones, including hardware and software aspects, were discussed briefly. Then, a research on the regulations for operating drones in Germany was made to determine the key rules and restrictions during conducting this project. Also, specific requirements for the final design of the delivery drone were analyzed and set. Because not all requirements were of the same level of importance, a prioritization method was adopted to have a clear strategy when comparing solutions.

In Chapter 4, possible hardware solutions were gathered and analyzed. As there were many drone systems available, a quick elimination strategy was made. Then, a comparison between the potential options was carried out based on the requirements set and the prioritization method from the previous chapter. As a result, the NXP Hovergames kit was decided as the adopted solution and further analysis of the drone details was done. Finally, possible software approaches were addressed and the suitable one was decided for the development.

In Chapter 5, the development steps were explained in detail. An overview of the system components and the building blocks was illustrated using block diagrams. The design started by having the system's hardware components assembled carefully. Then, the environment's setup was done, e.g., installing the operating system and necessary software applications. The used software programs and frameworks used were briefly discussed as well. After that, the PX4 software was flashed on the FMU successfully. QGC was used to complete the configuration and calibration of the drone to be ready to fly. In addition, MAVSDK Python API was used for coding and the logic was demonstrated graphically by a flow chart. Lastly, issues encountered during development were addressed as well.

In Chapter 6, details about the final drone system were presented, e.g., weight and software version. A number of flying attempts were discussed and the behavior observation was noted along with providing pictures of the related drone setup. As the behavior was not as expected at the beginning, troubleshooting steps were briefly mentioned and the slight improvement was addressed as well. Due to the available room for operating the drone, it was not enough to test all capabilities of the drone. In addition, the "Flight Review" tool was used to analyze the behavior of the flight attempt and consequently, future improvements were suggested. Furthermore, actual code testing was not recommended due to the possible risk from the unstable behavior and the limited space but it was partially tested without flying the drone. Finally, the fulfillment of the thesis' requirements was discussed based on the final results.

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Erklärung zur selbstständigen Bearbeitung

Hiermit versichere ich, dass ich die vorliegende Arbeit ohne fremde Hilfe selbständig verfasst und nur die angegebenen Hilfsmittel benutzt habe. Wörtlich oder dem Sinn nach aus anderen Werken entnommene Stellen sind unter Angabe der Quellen kenntlich gemacht.

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