POLITECNICO DI TORINO

Master Degree Course in Mechatronic Engineering

Master Degree Thesis

Implementation of an Ultralight Autopilot Drone for Service Robotics

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Abstract

According to the International Federation of Robotics any robot that operates autonomously or semi-autonomously to help the human being in his activities (excluding manufacturing) is a service robot. Today the use of drones has grown exponentially for different types of applications, including service robotics.
In this thesis, after a brief introduction on the regulation and classification of UAVs, the main sizing criteria of each component of a multirotor will be shown.
Starting from the design constraints and a state of the art of the main flight controllers, the hardware and firmware components chosen for the implementation of an autopilot quadcopter under 250 grams will be described. The sizing of the components will be strongly influenced by the weight of each of them and will be flanked by a test on the motor / propeller coupling to evaluate the performance and then to choose the most suitable devices for the purpose. Once the Pixracer FC has been identified as the best flight controller for the project, the PX4 firmware and the related software for remote control (Mission Planner and QgraounControl) will be described. Finally, after the assembly phase, the evaluation tests of the performance of the aircraft, the problems encountered and the possible solutions and improvements will be described.

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List of Acronyms

AC Alternating Current

API Application Programming Interface

APM ArduPilot Mega

BSD Berkeley Software Distribution

CAN Controller Area Network

CF Carbon Fiber

CPU Central Processing Unit

DC Direct Current

EASA European Aviation Safety Agency

EKF Extended Kalman Filter

ENAC Ente Nazionale per l'Aviazione Civile

ESC Electronic Speed Controller

FC Flight Controller

FPV First Person View

GPS Global Positioning System

GCS Ground Control Station

GLONASS Global Navigation Satellite System

HDOP Horizontal Dilution of Precision

IMU Inertial Measurement Unit

IFR International Federation of Robotics

LiPo Lithium Polymer

MAVlink Micro Air Vehicle Communication Protocol

MTOW Maximum Take Off Weight

OEM Original Equipment Manufacturer

OS Operating System

PCB Printed Circuit Board

PLA Polylactic Acid

POSIX Portable Operating System Interface for Unix

PWM Pulse-Width Modulation

QGC QGroundControl

RAM Random Access Memory

RC Radio Control

RHPC Remote Host Configuration Protocol

ROS Robot Operating System

SPI Serial Peripheral Interface

TOF Time of Flight

UART Universal Asynchronous Receiver-Transmitter

UAS Unmanned Aerial System

UAV Unmanned Aerial Vehicle

UDP User Datagram Protocol

uORB Micro Object Request Broker

USB Universal Serial Bus

VTOL Vertical Take Off and Landing

Chapter 1

Introduction

1.1 Service robotics

Robotics in the industrial sector is now a well-established and consolidated reality that uses technologies widely used in all modern companies. The consequent evolution of industrial robotics, is called service robotics, which is characterized by being currently in a phase of major expansion and is one of the most promising emerging technology trends. The term "service robot" does not have a strict technical definition but the International Federation of Robotics (IFR) has proposed a tentative definition:

"A service robot is a robot which operates semi- or fully autonomously to perform services useful to the well-being of humans and equipment, excluding manufacturing operations".

Service robotics thus defines a new class of intelligent robots able to operate both in working and domestic contexts with the aim of increasing the quality of life of the human being by avoiding exposure to risk factors and facilitating daily operations. The main applications of service robotics are represented by rescue and safety operations performed by drones and underwater robots; professional cleaning, to build and demolish urban infrastructures, for archaeological investigation, for inspection and maintenance, robots in the medical field for surgery and medical rehabilitation, in logistics and precision agriculture. The main types of robots suitable for this type of applications are rovers, submarines and UAVs (unmanned aerial vehicles).

1.2 Drones for service robotics

Thanks to their adaptability and versatility UAVs are used in different fields and applications and in recent years their use has increased considerably. Commonly known as drones, they are able to perform different applications even in critical situations with different objectives. For all these reasons the UAVs are protagonists of service robotics[1]. They are used for:

- **Saving life:** a drone can intervene in a disaster environment by providing first-class services without endangering the lives of life-saving operators.

- **Forecast of hurricanes:** a drone can reach areas subject to devastating meteorological events in order to collect useful data for the study and forecasts of similar events in the future.
- **Infrastructure maintenance:** a drone can be used by a specialized operator to assess the condition of an infrastructure thus avoiding costly and risky operations for buildings such as bridges and skyscrapers.
- **Agriculture monitoring:** farmers can use drones to monitor, irrigate, seed and care for their crops in general.
- **Support law enforcement:** drones can be used to perform surveillance operations, accident investigation, suspect tracking and crowd monitoring.
- **Aerial photography:** drones allow low-cost and risk-free aerial shooting even for harsh and hazardous environments.
- **Packages Delivery:** drones can be used as a means of delivery for small-sized packages.
- **3D mapping:** drones can be used to capture images and scans of a territory and then process them in three-dimensional maps.

1.3 UAVs classification

There are different types of UAVs that are classified according to different parameters. The most important classification is shown below[2]:

- **Fixed wing:** this type of aircrafts are equipped with a fixed wing and a rotor positioned on the front or back; they are able to cover long distances having a high autonomy but they are not able to take off and land vertically (they need a certain space).

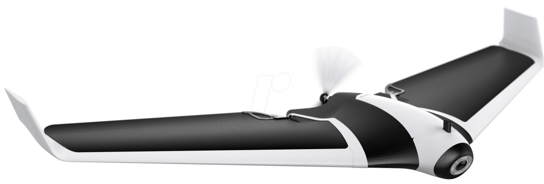


Figure 1.1: Fixed wing UAV (Parrot ® Disco)

- **Single rotor:** These UAVs have a single propeller positioned in the middle. They are able to take off and land vertically but are difficult to pilot.

Figure 1.2: Single rotor UAV (Prodrone ®)

- **Multi-rotor:** This is the most common category. Multirotors can have two or more propellers (bicopter, quadcopter, hexacopter and so on). They can take off and land vertically and are able to work in different conditions for various types of applications.

Figure 1.3: Multi-rotor (quadcopter) UAV (Intel ®)

- **Fixed-wing hybrid:** This category is born as a hybrid between the fixed wing and the multi-rotor category. This model of aircraft assume a similar behavior to the multi-rotors during take-off and landing and similar to a fixed wing during the flight phase. They are therefore able to travel long distances and take off and land vertically.

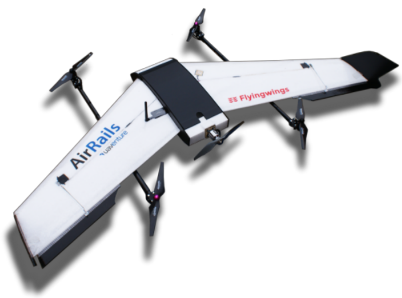


Figure 1.4: Fixed-wing hybrid UAV (Flyingwings ®)

1.4 Why an ultralight drone

Civil aviation security management is coordinated by the European Aviation Safety Agency (EASA). In addition to carry out monitoring activities, it issues certifications, regulations and standardization. The AESA agency is also responsible for collecting and processing data, providing advice on civil aviation laws and collaborating with various aeronautical authorities.[3]
In one of the latest releases of the European regulation on the use of UAVs, EASA has introduced a new category of aircraft according to the MTOW called Open Category A1 C0. This class of aircraft includes all the UAVs with MTOW less than 250 grams and therefore do not require registration or possession of an electronic on-board identification system. Drones belonging to this category can therefore be used freely in compliance with the flight rules, without any distinction between recreational and professional use [4]. Therefore, the main objective of this thesis is to design and build an autopilot quadcopter with a MTOW of less than 250 grams for service robotics applications.

<table>
<tr><th rowspan="2">Subcategory</th><th colspan="4">UAS</th></tr>
<tr><th>Class</th><th>MTOW</th><th>Electronic ID/
geo awareness</th><th>UAS operation
registration</th></tr>
<tr><td rowspan="2">A1</td><td>C0</td><td>< 250 g</td><td>No</td><td>No</td></tr>
<tr><td>C1</td><td>< 900 g</td><td rowspan="3">Yes</td><td rowspan="4">Yes</td></tr>
<tr><td>A2</td><td>C2</td><td>< 4 kg</td></tr>
<tr><td rowspan="2">A3</td><td>C3</td><td rowspan="2">< 25 kg</td></tr>
<tr><td>C4</td><td>If required from the
zone of operation</td></tr>
</table>

Table 1.1: EASA UAVs classification

Chapter 2

Drone anatomy

A UAV is an aircraft without a pilot aboard able to move by remote control of an operator using a remote controller or an integrated autopilot system. A system composed by control station, UAV and communications system is called UAS (Unmanned Aerial System).

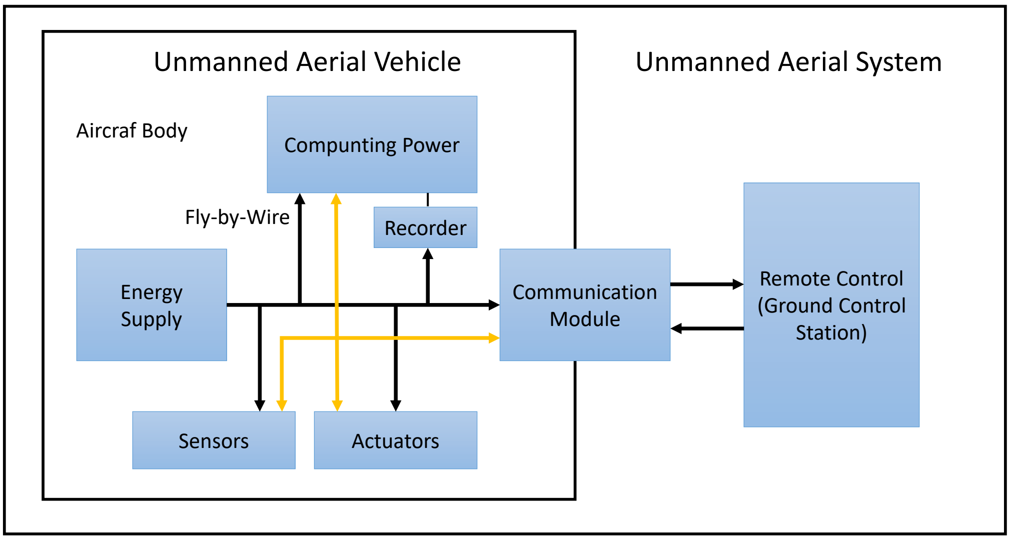


Figure 2.1: UAS schematic

Taking a quadcopter as reference, a drone is composed of the following components:

- Frame
- Flight controller
- GPS
- Motors
- Propellers
- ESC
- Telemetry module
- Receiver
- Battery
- Additional components (payload)

2.1 Frame

The frame is the supporting structure of the whole aircraft. It aims to support the various components in the right position, to guarantee stiffness, stability and the most precise weight balance as possible. The size of a quadcopter is simply the distance along the diagonal between two motors. The choice of the frame size is very important for the design of a drone as it affects on: max propeller size, motor size, moment of inertia of the aircraft, air resistance and total weight.
The frame can take different shapes and layouts depending on the arrangement of the arms with respect to the main body; the main configurations are H, X and X+.

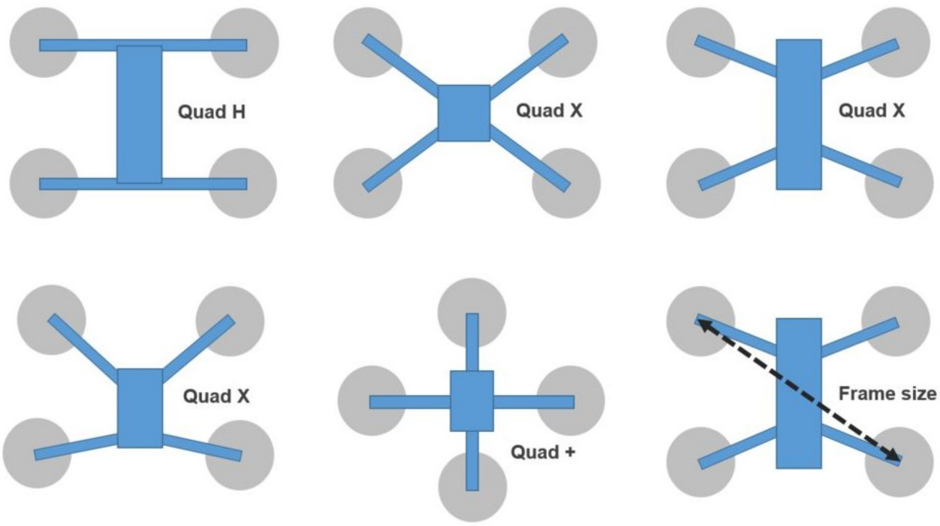


Figure 2.2: Common frame shapes and size indication

Therefore, it must be chosen according to the application that the aircraft has to perform (aerial photography, racing, packages delivery, etc). The most used materials for the construction of the frames are: Wood, 3D printed plastic, injection molded plastic, fiber glass, aluminum, PVC pipes or carbon fiber (the most common solution for the characteristics of this material as stiffness, strength and lightness) [5].

2.2 Flight controller

The flight controller is the brain of the aircraft. It is able to measure the movements of the drone through sensors such as gyroscopes, accelerometer, barometric pressure sensor and compass (IMU). The board hold the firmware that elaborates the data collected by these sensors and through particular algorithms it computes how fast the motor should be spun for the craft to behave as the pilot is instructing via stick inputs on the TX. All the components of the drone are therefore connected directly or indirectly to the flight controller which, through the telemetry system, communicates with the ground control station to receive commands and send the collected data[5].

Figure 2.3: Pixhawk V2 flight controller

2.3 GPS

The global position system is a satellite navigation system that provides information about the position and time of any point on the Earth. Localization occurs by transmitting a radio signal from each satellite and processing the signals received by the receiver. The integration of a GPS module on a drone, not only allows to monitor the position and speed of the aircraft but also to perform operations such as:

- **Position Hold:** the drone maintains a fixed position and altitude.
- **Return to home:** during take-off, the drone memorizes its coordinates. When this function is activated, the aircraft automatically returns to the starting point to make a landing.
- **Autonomous flight:** the flight path of the drone is established through GPS waypoints that define the trajectory. Once this mode is started, the drone will follow this route thanks to the autopilot[6].

2.4 Motors

Motors are some of the most important components of a drone because they are responsible, coupled to the propellers, of the thrust generation. The motor-prop coupling is in fact fundamental for optimizing the performance of the aircraft. Motors and propellers must therefore be sized in order to generate a thrust that guarantees good stability and response of the drone; The thrust must be at least double of the total weight of the aircraft (if the drone has a mass of 500 grams the thrust must be at least 1 kg, 250 grams per motor).
Brushless motors are classified by using 4 digit (AABB) which describe their dimensions in millimeters. The first two indicate the stator width (or stator diameter) while the second the stator height. Taller stator means more power at higher RPM while wider stator means more torque at lower RPM.
The anatomy of the motor is described by an abbreviation of the type: 12N14P. N stands for number of electromagnets in the stator and P stands for number of permanent magnets in the bell. Then the 12N14P code means that the motor is built with 12 electromagnets

in the stator and 14 permanent magnets in the bell.
Another important parameter of a motor is the KV factor (RPM per volt). It's an important parameter of brushless motors, which indicates how much the rotation speed increase in relation to the voltage. (for example, when powering a 3100 KV motor with a 2S LiPo battery (7.4 V), it will spin at around 22940 RPM)[7].

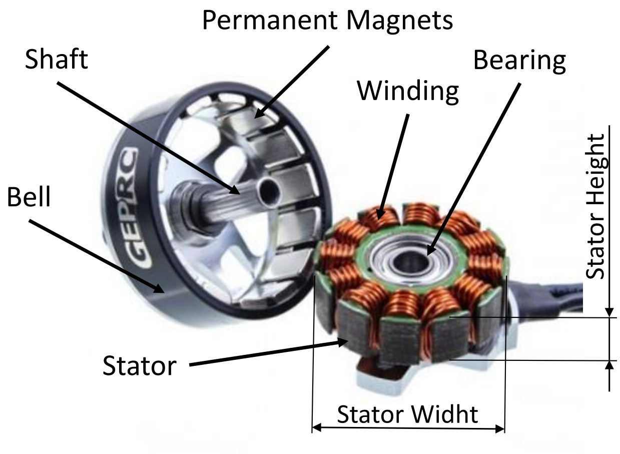


Figure 2.4: 12N14P brushless motor anatomy (Greprc ®)

2.5 Propellers

Propellers are directly responsible of the thrust generation. By rotating faster they are able to move more air and therefore generate more thrust.
The main features of a propeller are length and pitch:

- The length of a propeller is the diameter of a disc the prop makes when it's spinning.
- Pitch can be defined as the travel distance of one single prop rotation.

If on one hand a propeller with a higher value of length and pitch generates more thrust, on the other it will require more energy to generate the rotation.
Propellers are classified according to two types of formats: L×P×B or LLPP×B (lenght, pitch, numeber of blades). For example 6×4.5 (also known as 6045) propellers are 6 inch long and has a pitch of 4.5 inch. 5x4x3 (sometimes 5040×3) is a 3-blade 5 inch propeller that has a pitch of 4 inch[8].

2.6 ESC

ESC stands for Electronic Speed Controller. As the name suggests, they take care of the regulation of the rotation speed of the motors. The ESC provides the optimum energy level to the motors by receiving an acceleration signal that comes from the controller as

input.
The maximum amount of continuous current which the ESC can safely handle is the "continuous current rating" while the higher current for which ESCs are usually designed to withstand for short periods of time is the "burst current rating"[9].
The motor, propeller and ESC system is called power train system. As these components work together, the sizing of the ESC must be performed taking into account the motor-propeller coupling and the absorbed current necessary for the generation of the required thrust. This procedure is usually carried out through the thrust data table that should be provided with any multi-rotor motors. An example of one such thrust data table for a MT1806 is given below:

Motor Type	Voltage (V)	Paddle size	Current (A)	Thrust (g)	Power (W)	Efficiency (g/W)	Speed (RPM)
MT1806-2280KV	7.4	5030 Carbon Fiber Prop	4.4	210	2.6	6.4	13530
		APC 6*4	6.8	280	50.3	5.6	12030
		5*4.5 three-blade prop	6.2	240	45.9	5.2	12330
	11.1	5030 Carbon Fiber Prop	8	380	88.8	4.3	18510
		APC 6*4	11.3	460	125.4	3.7	15160
		5*4.5 three-blade prop	10.6	410	117.7	3.5	15910

Table 2.1: Thrust data table for a MT1806 motor

Depending on the required thrust (must be at least twice the weight of the drone), it is possible to derive the current absorbed by that motor with different types of propellers and batteries. Once this value is obtained, it is possible to size the ESC choosing a current value slightly higher than that obtained from the table. For example:
A 500-gram quadcopter equipped with the MT1806-2280KV needs a thrust of at least 1 kg (250 grams per motor). From the table it is deduced that a thrust of 280 grams per motor can be obtained by using the APC 6×4 propeller and a 7.4 V (2S) battery. The current absorbed with this configuration is equal to 6.8 A, therefore a 10 or 12 Amps ESC will be needed[10].

2.7 Telemetry module

Telemetry is a technology that allows data transmission from remote or inaccessible points to a control station. The use of a telemetry module on a drone is not required but can be very useful especially for certain types of applications. The use of telemetry involves the installation of a device on board and one on the ground connected to the ground station.[11]. The communication takes place on different frequencies depending on the region (433 MHz for Europe and 915 MHz for US).

2.8 Receiver

The commands sent by the transmitter on the ground are received by the radio receiver. This device sends signals to the flight controller that converts them into specific actions to control the aircraft. Radio communication protocols can be classified into two groups:

- TX Protocols between Radio Transmitter and Radio Receiver.
- RX Protocols between Radio Receiver and Flight Controller.

TX Protocols are in most cases specific to brands (FrSky: D8, D16, LR12; Spektrum: DSM, DSM2, DSMX; FlySky: AFHDS, AFHDS 2A; Futaba: FASST; Hitec: A-FHSS; Devo: Hi-Sky) while for RX Protocols, some of them are universal (PCM, PWM, PPM, SBUS).
Therefore, to work correctly, the receivers and the transmitter must speak to the same language. This means that the two devices must belong to the same brand. But there are some exceptions of devices of different brands which are able to communicate because they use the same protocol. Therefore, The RC and TX must work on the same frequency[12].

2.9 Battery

The battery (LiPo) is the energy source of the whole quadcopter. It is characterized by a high energy density, high discharge rate and consists of individual cells connected in series with each other. Each cell has a nominal voltage of 3.7 V for this reason the battery voltage is indicated with the letter S, which indicates the number of cells inside the battery (1S = 3.7 V; 2S = 7.4 V; 3S = 11.1 V etc)[13].
The battery capacity instead is indicated in mAh. Choosing a high capacity battery means increasing the performance in terms of TOF but on the other hand it means increasing the weight and the physical dimensions of the device[14].
Another important parameter that characterizes a LiPo battery is the C rating which indicates the discharge rate. By knowing this value it is possible to compute the maximum discharge current of the battery:

$$Maximum\ Discharge\ Current = C\text{-}Rating \times Capacity \tag{2.1}$$

For example an 1300 mAh 50 C battery has an estimated continuous maximum discharge current of 65 A.
Sometimes some batteries may have two C-ratings on the label: the continuous and the burst rate. The second is only applicable for a short period of time (usually 10 s).
So the parameters to be evaluated to size a battery are not just voltage and capacity. The C-rate must be chosen to ensure that the current required by the motors is lower than the maximum discharge current. For example:
taking into consideration the example given in paragraph 2.6, the current absorbed by

each motor is 6.8 A, therefore the total current will be 27.2 A (6.8×4). The capacity and C-rating of the battery must therefore be higher than this value. In fact, if you choose a 1300 mHa 55 C battery, the maximum discharge current will be:

$$Maximum\ Discharge\ Current = 55 \cdot 1.3 = 71.5A > 27.2A \tag{2.2}$$

Once the battery, motors, propellers and ESC have been chosen, it will also be possible to compute the TOF of the aircraft by consulting the thrust table of the motor:

$$TOF = \frac{Battery\ Capacity}{Current\ absorbed\ by\ motors} \tag{2.3}$$

2.10 Additional components

Depending on the type of application that the drone must be able to perform, it is possible to equip the drone with other components such as battery alarm, gimball, camera etc. The video streaming system is definitely the most used equipment and it is composed of the following components:

- Camera
- Video TX
- Antenna

The equipment of this system on the drone allows the pilot on the ground to have a view of the aircraft in first person and in real time. This system allows to operate also in case of visual loss of the drone and to carry out visual monitoring operations.

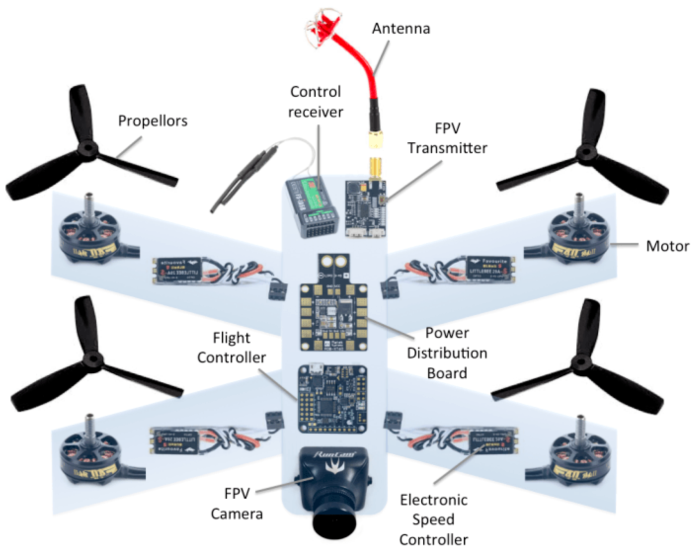


Figure 2.5: Drone anatomy

Chapter 3

Design

As reported in the paragraph 1.4, the aim of this thesis is to design and build a quadcopter with a mass of less than 250 grams intended for service robotics applications. The procedure used was to start from the design constraints to obtain a state of the art of flight controllers currently available. Once the most appropriate controller has been chosen, the parts have been sized and tested accordingly, always taking into consideration the weight of each of them.

3.1 Design constraints

That of weight is not the only constraint of the project. The drone must in fact comply with the following specifications:

- **Autopilot drone:** the term autopilot refers to a system able to manage part of the movement of an aircraft (trajectory management, speed control, height maintenance, etc.) without the constant intervention of an operator. An autopilot drone then allows the operator to focus on other aspects of the mission such as telemetry control, data processing or video monitoring. It is important to underline that this system does not completely replace the control by an operator but it simply facilitates its use[15].

- **Open platform:** The whole system must be based on open standards (such as published and fully documented external API). An open platform system allows users to intervene and improve the project proposed by the seller who gives them the means to do it. In this way the project will always be growing and updated with current technology.

- **MAVLink communication protocol:** The MAVlink communication protocol (Micro Air Vehicle Link) is a system created specifically for vehicles with remote piloting systems that allows communication between aircraft and ground control station but also between devices inside the vehicle. Thanks to this protocol it is possible to send and receive data such as position, height, speed, orientation, etc[16].

- **ROS compatible:** ROS (Robot Operating System) is the operating system that provides developers with the necessary tools to create robot control applications[17]. The communication between UAVs and running ROS ground control stations, is performed by using a special package called MAVROS. This package provides communication drivers for different autopilots with MAVLink communication protocol and provides a MAVLink UDP bridge for ground control stations[18].

- **Ultralight:** This is the most difficult constraint to comply. The quadcopter must have a MTOW of less than 250 grams in order to be classified as an A1C0 aircraft. Therefore all the components must be sized in order to obtain the maximum performance (in terms of TOF) with a very low total mass.

3.2 Firmware

The starting point of the project was initially to identify the available firmware able to satisfy the design constraints described in the previous paragraph. Most of the constraints can be complied by simply choosing a suitable firmware. The two most used flight management firmware of a multirotor are Ardupilot and PX4. Both can be used on most available flight controllers:

- **Ardupilot:** Ardupilot is definitely one of the most used application in the field of autopilot firmware. It can be installed not only on aircraft such as drones or airplanes but also on land and marine vehicles such as rovers, boats and submarines. Being very used Ardupilot is also one of the most tested and continuously evolving software (it is open source code based). The software suite is installed in aircraft from many OEM UAV companies, such as 3DR, jDrones, PrecisionHawk, AgEagle and Kespry. It is also used for testing and development by several large institutions and corporations such as NASA, Intel and Insitu/Boeing, as well as countless colleges and universities around the world [19].

- **PX4:** PX4 autopilot is an open-source autopilot system oriented toward inexpensive autonomous aircraft. Low cost and availability enable hobbyist use in small remotely piloted aircraft. The project started in 2009 and is being further developed and used at Computer Vision and Geometry Lab of ETH Zurich (Swiss Federal Institute of Technology) and supported by the Autonomous Systems Lab and the Automatic Control Laboratory. Several vendors are currently producing PX4 autopilots and accessories[20].

Ardupilot and PX4 fully comply the design constraints as they are both open platform and autopilot firmware and use the MAVLink communication protocol that can be managed by ROS through the MAVROS package.

3.3 Flight controller; state of the art

Once the most suitable firmware for the project have been identified, the next step was performing an analysis of the compatible flight controllers. The boards compatible with Ardupilot and PX4 firmware are listed in the following table:

Flight Controller	Firmware Compatibility	
	Ardupilot	PX4
mRo Pixhawk	✓	✓
Pixhawk 2	✓	✓
Pixhawk mini	✓	✓
mRo Pixracer	✓	✓
Pixhawk 4	✓	✓
Pixhawk v5	✓	✓
Beagle Bone Blue	✓	
Erle-Brain 3	✓	
F4BY	✓	
OpenPilot Revolution	✓	
PXFmini RPi Zero Shield	✓	
TauLabs Sparky2	✓	

Table 3.1: Flight controller firmware compatibility

All the technical specifications of the aforementioned controllers are given in the appendix A.
The choice of the flight controller must therefore be performed taking into consideration not only the technical specifications but also the physical ones; in particular the weight:

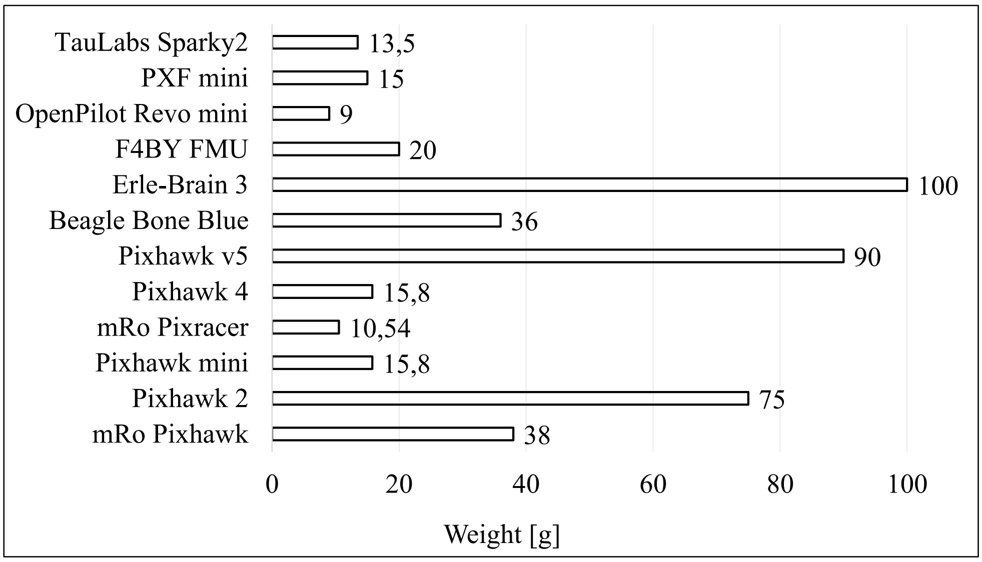


Figure 3.1: Flight controllers weight analysis

Figure 3.1 allows to compare the weight of each flight controller so as to exclude the heavier ones. Among the controllers of less than 20 grams, the most appropriate to this project is definitely the Pixracer; In fact, it represents the best product in terms of technical specifications with the lowest weight. It is still widely used for different types of applications and continuously updated by the manufacturer.

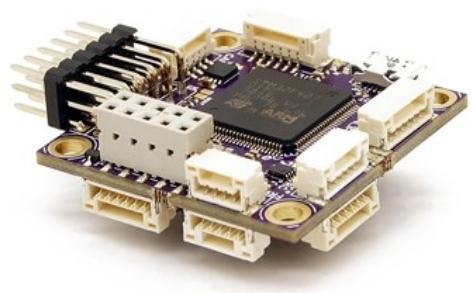


Figure 3.2: Pixracer flight controller (mRobotics ®)

3.4 Peripherals

Once the flight controller and the corresponding firmware have been assigned, the rest of the components have been sized as follows:

3.4.1 mRo ® PixRacer R15 DIY multicopter kit

mRobotics ® offers a Pixracer-based starter kit with some of the main components for building a drone. The kit includes:

- **PixRacer flight controller:** contrary to how the name suggests, Pixracer is not just a "race" controller, but it is a real autopilot. It is indeed an evolution of the original PixHawk but redesigned in terms of size and built so that it can perform typical operations of an autopilot like autolanding and full navigation but also real drone races.

- **mRo ® GPS u-Blox Neo-M8N Dual Compass LIS3MDL+ IST8310:** the mRo GPS NEO-M8N is a robust and professional GPS system capable of simultaneously detecting US (GPS), Russian (GLONASS) and European (Galileo) constellations. It is equipped with an accurate position and a fast satellite acquisition system. The manufacturer declares an average HDOP of 0.6.

- **10S Power module (ACSP5):** the ACSP5 module is a power supply module with a very low noise level, current and voltage detector and a very small size.
- **mRo ® SiK Telemetry Radio V2 433Mhz:** this module allows the communication of better than 300 m (depends on the antena) and works using an open source firmware optimized for the use of the Mavlink communication protocol and the main ground control stations and UAVs.

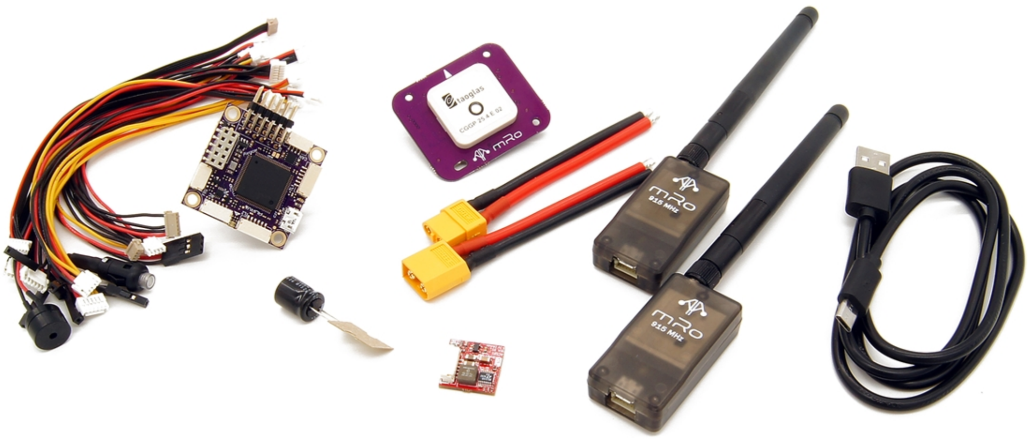


Figure 3.3: Pixracer starter kit (mRobotics ®)

3.4.2 Motors, propellers and ESC

Motor and propellers must always be chosen together in order to evaluate the performance of their coupling as described in paragraph 2.4 and 2.5. For this project the following components have been used:

- **Tiger Motor MT-1306-10 3100 KV:** the main features of these motors are definitely the efficiency and weight (only 11.2 grams). The main technical specifications and the thrust table test declared by manufacturer are described below:

Technical datas	
KV	3100
Configuration	9N12P
Stator Diameter	13 mm
Stator Length	6 mm
Shaft Diameter	2 mm
Motor Dimensions	ϕ 17.7×15 mm
Weight	11.2 g
ldle current (10) @ 10v	0.2 A
No. of Cells	1-2S
Max Continuous current 180S	6 A
Max Continuous Power 180S	44 W
Max. efficiency current	(1.5-4A) >71%
Internal Resistance	0.062 Ω

Table 3.2: Tiger Motor ® MT-1306-10 3100 KV technical specifications

Tested with T-motor 6 A ESC					
Prop	**Voltage [V]**	**Current [A]**	**Power [W]**	**Thrust [g]**	**Efficiency [g/W]**
4025	7	3.2	22.4	123	5.49
	7.4	3.4	25.16	131	5.21
5030	7	4.8	33.6	171	5.09
	7.4	5.2	38.48	179	4.65
6030	7	5.7	39.9	205	5.14
	7.4	6.2	45.88	218	4.75

Table 3.3: Tiger Motor ® MT-1306-10 3100 KV thrust table

Figure 3.4: Tiger Motor ® MT 1306-10 3100 KV

- **Tiger Motor ® 6020 carbon fiber propellers:** These propellers are designed specifically for multirotors and with a suitable motor they are able to generate a very high thrust. They are also very efficient, light and resistant because they are made of carbon fiber.

Figure 3.5: Tiger Motor ® 6020 carbon fiber propellers

- **Lumenier ® Mini BLHeli 12A 4 in 1 OPTO ESC DSHOT:** Usually in a quadcopter each motor is associated with an ESC mounted on each arm of the drone; however, there are some speed controllers grouped in a single board. The use of this type of device allows to obtain a light and compact hardware configuration. Precisely for this reason the model Lumenier Mini 4 in 1 has been chosen. This device is in fact small size (27x27x2 mm, 20x20mm mounting holes) and light (20 grams) and is able to handle continuous currents up to 12 A with a burst current of 18 A. Positioning it in the center of the multirotor also allows to maintain a correct weight distribution of the drone.

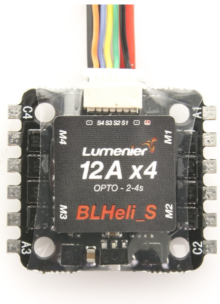


Figure 3.6: Lumenier ® Mini BLHeli 12A 4 in 1 OPTO ESC

3.4.3 Receiver

The choice of a receiver compared to another is not so essential for the success of the project. The only aspect to be taken into consideration is the compatibility with the available radio transmitters. For this project the X4R-SB-3/16 Channel from FrSky ® device has been chosen. This device is very small and light (40x22.5x6 mm, 5.8 g) covers over 1.5 km and it is provided by 16 channels S-BUS and 3 Channels PWM.

Figure 3.7: FrSky ® X4R-SB-3/16 Channel receiver

3.4.4 Battery

According to the technical specifications of the MT-1306 motor and Lumenier mini ESC, the system must work with a 2S or 3S LiPo battery. Furthermore the capacity must be chosen in order to maximize the performance in terms of TOF while keeping the weight low. The battery is the heaviest component of the whole aircraft and enlarging its capacity or the number of cells means increasing performance on one hand but also the weight on the other. For these reasons the choice of the battery has not been univocal but a set of

3 batteries (from Thunderpower ®) with different specifications has been chosen in order to be able to face the various possible problems that can arise from the use of a battery rather than the other:

- **TP870-2SE55J 870mAh 2-Cell/2S 7.4V Elite 55C LiPo, JST**
- **TP1300-2SE55 1300mAh 2-Cell/2S 7.4V Elite 55C LiPo**
- **TP870-3SE55J 870mAh 3-Cell/3S 11.1V Elite 55C LiPo, JST**

Specifications	**Battery set**		
	TP870-2SE55J	**TP1300-2SE55**	**TP870-3SE55J**
Capacity	870 mAh	1300 mAh	870 mAh
N° of cells	2S	2S	3S
Max Charge	8C	8C	8C
Max Cont. Discharge	55C	55C	55C
Max Charge Current	6.9 A	10.4 A	6.9 A
Max Burst Discharge	100C	100C	100C
Max Burst Current	95.7 A	143 A	95.7 A
Weight	49 g	74 g	73 g
Max Cont. Current	47.8 A	71.5 A	47.8 A
Dimensions	14 x 30 x 62 mm	12 x 30 x 100 mm	20 x 30 x 62 mm

Table 3.4: Thunderpower ® battery set technical specifications

3.4.5 Frame

The frame is the skeleton of the aircraft and its task is to support all the peripherals. All hardware components must therefore be placed on top of it in order to distribute the weight uniformly. For this project a three-layer frame has been chosen in order to be able to accommodate all the components at the center of the drone by absorbing the vibrations thanks to the anti-vibration rubbers.
The total mass of the frame is 61.25 grams but can be reduced by removing two of the three layers. In this way a "lightened version" of the frame is obtained (40.25 grams) that could be useful in case of an unforeseen overweight of the total weight of the aircraft.

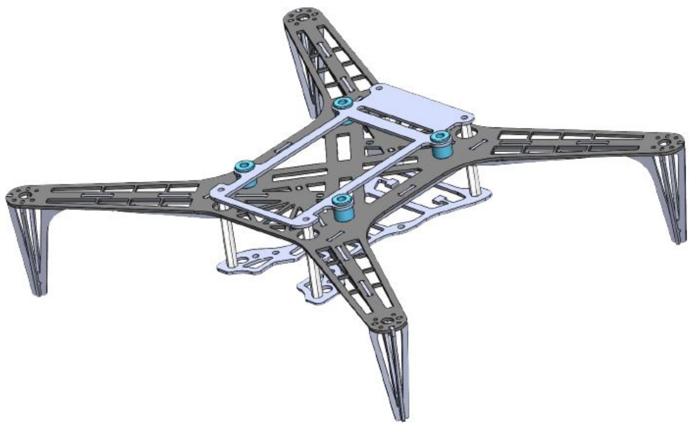
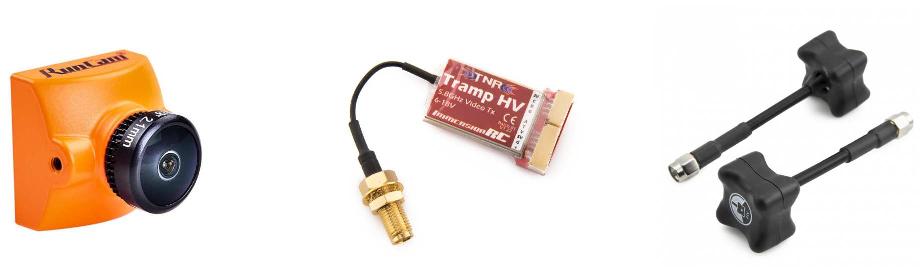


Figure 3.8: Three layer frame

3.4.6 Payload

One of the fundamental skills of a UAV is to be able to transmit on the screen what the drone sees. A video transmission system is necessary to provide the drone with eyes. The system chosen for this project is composed by the following components:

- **Runcam Racer 4:3 Micro FPV Camera**
- **ImmersionRC Tramp HV 5.8GHz Video Tx**
- **TBS Triumph 5.8GHz RHCP FPV Antenna Set**
- **FXT 5" Diversity Monitor** (on the ground station)



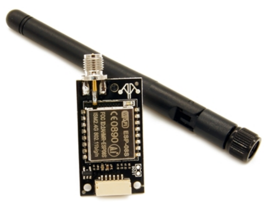
(a) (b) (c)

Figure 3.9: Runcam ® camera (a), Tramp ® video TX (b), Triumph ® antenna (c)

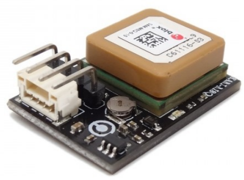
3.4.7 Alternative components

As an alternative to some of the components that have been described in the previous paragraphs, other devices that can reduce the total weight of the drone have been included in the list of components:

- **mRo ® WiFi Module V1.0 - ESP8266:** Telemetry could be impemented by adding a wifi module to the flight controller; through the installation of the WiFi module ESP8266 it is in fact possible to establish UDP connection between the drone and ground control station saving a considerable amount of weight (the only drawback is the reduction of the transmission range).
- **Ublox ® SAM-M8Q GPS module:** the main features of this component are size and weight. It covers a surface of 20x28 mm and weighs only 8 g. The use of this device would certainly allow a drastic reduction of the MTOW.
- **Diatone blade 200 carbon fiber frame:** This is a 200 mm racing frame made from 3K carbon fiber 2 mm thick. Also in this case the main advantage is the weight: only 27.5 g.



(a)



(b)

(c)

Figure 3.10: mRo ® WiFi Module ESP8266 (a), Ublox ® SAM-M8Q GPS module (b), Diatone blade 200 carbon fiber frame (c)

3.5 Weight analysis

As specified by the design constraints, the drone must have an MTOW under 250 grams to be classified as an aircraft belonging to the A1C0 category. For this reason it was necessary to carry out an accurate analysis of the weight of each component that has been described in the previous paragraphs in order to compute the total mass of the aircraft.

Component	**Model**	**Quantity**	**Weight [g]**	**Total Weight [4]**
FC	mRo Pixracer	1	10.54	10.54
Power Module	ACSP5	1	17	17
GPS	u-Blox Neo-M8N Dual Compass	1	33	33
	Ublox SAM-M8Q	1	8	8
Telemetry	mRo SiK Telemetry Radio V2	1	20	20
	mRo WiFi Module	1	10	10
Motor	T- Motor MT-1306-10 3100 KV	4	11.2	44.8
Prop	T-motor 6020 Carbon Fiber	4	2.2	8.8
ESC	Lumenier Mini BLHeli 12A 4 in 1	1	20	20
Receiver	FrSky X4R-SB-3/16 Channel	1	5.8	5.8
Battery	TP870-2SE55J	1	49	49
	TP1300-2SE55	1	74	74
	TP870-3SE55J	1	73	73
Frame	Three Layer Frame	1	61.25	61.25
	Three Layer Frame Light Version	1	40.25	40.25
	Diatone Blade 200	1	27.5	27.5
Payload	Runcam Racer	1	5.5	21
	ImmersionRC Tramp TX	1	4	
	Triumph Antenna	1	11.5	

Table 3.5: Weight of the components

The best hardware configuration to keep the MTOW under 250 grams maximizing performance (without considering the payload) is composed of the following components:

Component	Model	Quantity	Weight [g]
FC	mRo Pixracer	1	10.54
Power Module	ACSP5	1	17
GPS	Ublox SAM-M8Q	1	8
Telemetry	mRo WiFi Module	1	10
Motor	T- Motor MT-1306-10 3100 KV	4	44.8
Prop	T-motor 6020 Carbon Fiber	4	8.8
ESC	Lumenier Mini BLHeli 12A 4 in 1	1	20
Battery	TP870-2SE55J	1	49
Receiver	FrSky X4R-SB-3/16 Channel	1	5.8
Frame	Three Layer Frame Light Version	1	40.25
		MTOW	**214.19**

Table 3.6: Hardware configuration weight analysis

The set of components shown in the previous table allows to obtain an MTOW around 215 grams. This value allowe to have a margin of 35 grams for payload and cables. Therefore the hardware configuration shown in table 3.6 is the definitive one for the evaluation of the practical tests.

3.6 eCalc tool

An useful tool for designing a multirotor is represented by the online tool called eCal. It is a web platform with a vast database of components that allows users to build and test a hardware configuration virtually. Using this tool it is possible to test not only multirotors but also airplanes, helicopters, jets and gearboxes[21]. By entering the data from table 3.6 the results shown in table 3.7 have been obtained:

Load [C]	**Hover TOF [min]**	**Power [W]**	**Temperature [°C]**	**Thrust/Weight**	**Thrust [g/W]**
45.39	14.7	60.6	31	4.9	11.33

Table 3.7: eCalc Tool results

The most significant values are the TOF and the thrust/weight ratio. The first describes the flight time in the hovering condition (that stationary condition for which the thrust generated by propellers is equal to the weight force of the aircraft). The second describes how match the drone is pushing in relation to its weight (2 is the minimum value for an appropriate control of the multirotor). Obviously these are only estimated values that just give an idea of the drone's performance but also give a good landmark to compare the experimental data.

Chapter 4

First test; motor and propeller coupling

The main target of this first test is to evaluate the performances of the Tiger Motor MT1306 3100 KV and the Tiger Motor CF 6020 propellers coupling comparing the obtained results with those provided by Ecalc Tool.

4.1 Introduction

The test has been implemented in two different fashions:

- Constant $V_N = 7.4$ V; varying PWM.
- Varying V_N; Constant PWM = 100 %

In both cases the thrust measurement has been carried out by push upwards (weight difference of a known initial mass) and downwards of the motor/propellers by means of a sling bar.

4.2 Setting

For this test an oversized ESC has been chosen in order to supply the current required by the motor. The speed controller, powered through a power supply, has been connected to the three phases of the motor according to the correct direction of ration and to a PWM signal generator to control the throttle of the motor also connected to a power supply (5 V). Channel 1 and 2 of the oscilloscope have been used to measure respectively voltage and current (through a current probe) provided by the power supply while channel 3 has been connected to one of the phases of the motor to measure the frequency of the electrical cycle.
The measured and computed parameters are listed below:

Measured values:

- Power P_{IN} [W]
- Voltage V [V]
- Current I [A]
- Starting thrust T_{start} [g]
- Final thrust T_{end} [g]
- Electrical frequency f_{el} [Hz]

Data:

- Number of poles $p = 12$
- Poles pair $p_p = 6$
- Air density $\rho = 1.225$ [Kg/m^3]
- Propeller lenght $D = 6$ in $= 0.1524$ m

Computed values:

- Real thrust $T_{real} = T_{end} - T_{start}$ [g]
- Trust $T = \frac{T_{real} \cdot 1000}{9.81}$ [N]
- Mechanical frequency $f_m = \frac{f_{el}}{p_p}$ [Hz]
- Angular velocity $\omega = f_m \cdot 60$ [RPM]
- $\mathrm{c_T}$ factor $c_T = \frac{T}{\rho f_m^2 D^4}$

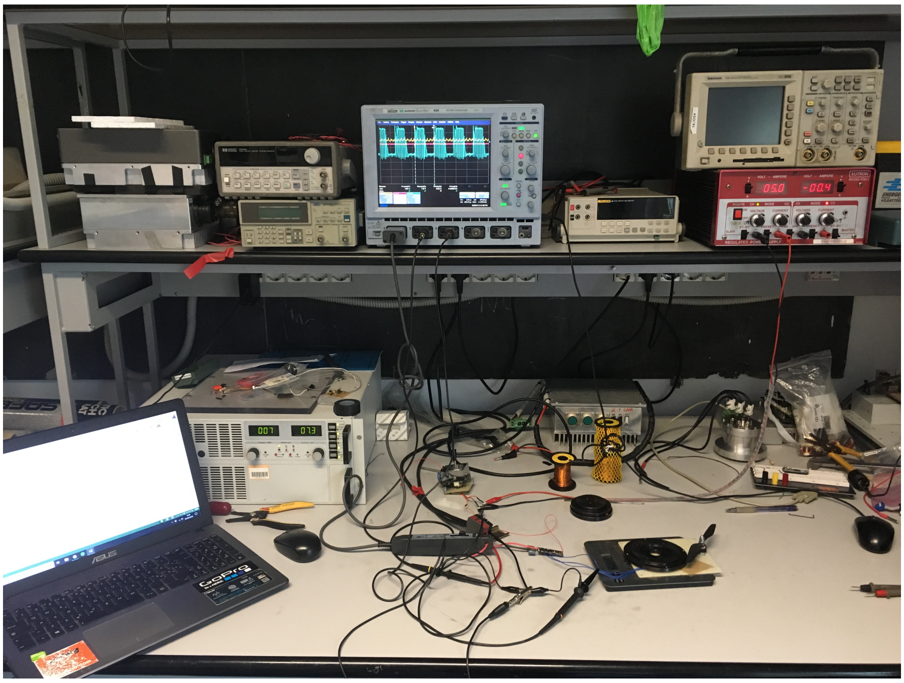


Figure 4.1: Test bench setting

4.3 V_N = 7.4 V; varying PWM

4.3.1 "Pulling thrust"

The first test has been performed by imposing a nominal voltage equal to 7.4 V (2S battery configuration) and by coupling the propeller to the motor in order to obtain an upward pulling effect (push up). Measurements have been made for several increasing throttle values via PWM signal.

P_{IN} [W]	V [V]	I [A]	T_{start} [g]	T_{end} [g]	T_{real} [g]	T [N]	f_{el} [Hz]	f_m [Hz]	ω_m [RPM]	c_T
2,6005	7,43	0,35	1690	1672	18	0,17658	487	81,16667	4870	0,040561
4,81	7,4	0,65	1690	1664	26	0,25506	606	101	6060	0,037838
8,732	7,4	1,18	1693	1653	40	0,3924	769	128,1667	7690	0,03615
12,025	7,4	1,625	1693	1642	51	0,50031	873	145,5	8730	0,035763
14,43	7,4	1,95	1693	1637	56	0,54936	920	153,3333	9200	0,03536
22,866	7,4	3,09	1693	1617	76	0,74556	1037	172,8333	10370	0,03777

Table 4.1: V_N = 7.4 V, varying PWM; pulling test measurements

4.3.2 "Pushing thrust"

The same operation has been repeated coupling the propeller to the motor in order to have a pushing effect (push down). This was possible by simply inverting the propeller coupling and the direction of rotation of the motor. The following results have been obtained:

P_{IN} [W]	V [V]	I [A]	T_{start} [g]	T_{end} [g]	T_{real} [g]	T [N]	f_{el} [Hz]	f_m [Hz]	ω_m [RPM]	c_T
2,1084	7,53	0,28	0	15	15	0,14715	421	70,16667	4210	0,04523
3,825	7,5	0,51	0	29	29	0,28449	562	93,66667	5620	0,049071
5,85	7,5	0,78	0	44	44	0,43164	672	112	6720	0,052073
8,85	7,5	1,18	0	61	61	0,59841	797	132,8333	7970	0,051323
13,482	7,49	1,8	0	83	83	0,81423	899	149,8333	8990	0,054885
18,5256	7,47	2,48	0	102	102	1,00062	1037	172,8333	10370	0,050692

Table 4.2: V_N = 7.4 V, varying PWM; pushing test measurements

4.3.3 Pulling thrust VS pushing thrust

Repeating the same procedure in two different thrust configurations has allowed to highlight a deviation from the real working conditions of the motor due to the low distance between propeller and ground in the “pulling” configuration (push upwards):

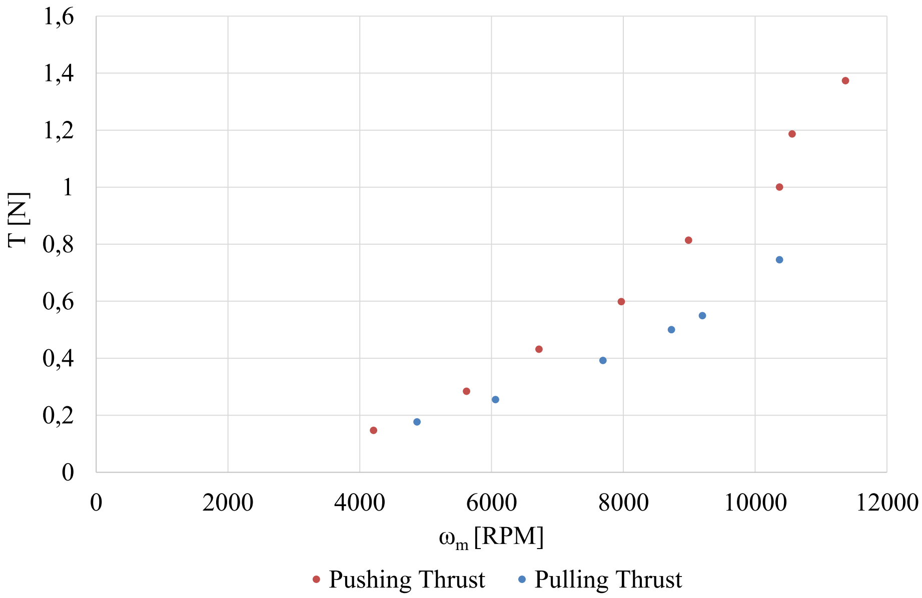


Figure 4.2: Thrust VS RPM (pushing VS pulling)

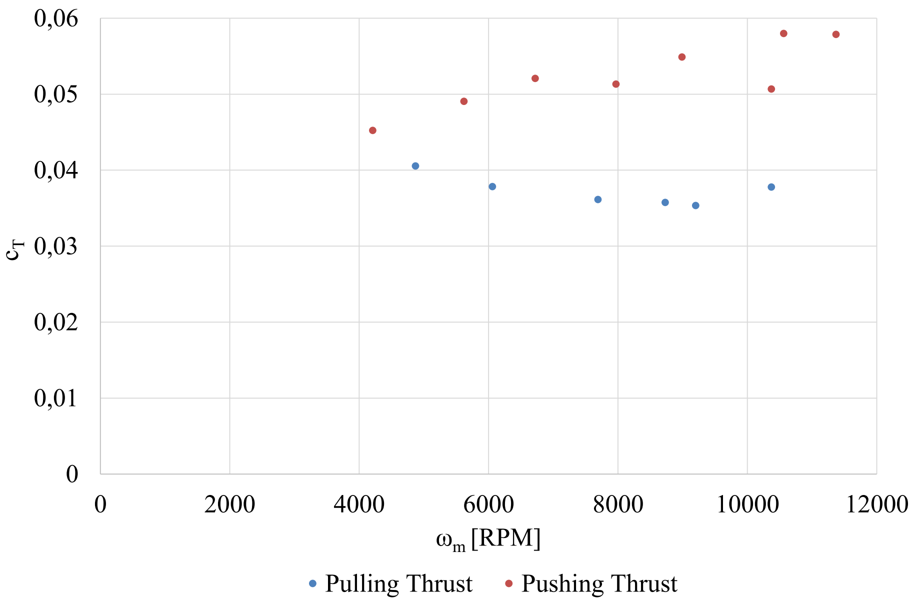


Figure 4.3: c_T VS RPM (pushing VS pulling)

As you can see from the figure 4.2 and 4.3, as the RMP value increases, the thrust obtained in the two configurations deviates more and more due to the high pressure air restricted in a small space in the “pulling” configuration. Indeed, in pushing configurations, higher thrust and c_T values have been measured at the same RPM because this effect is not present in the pushing configuration.

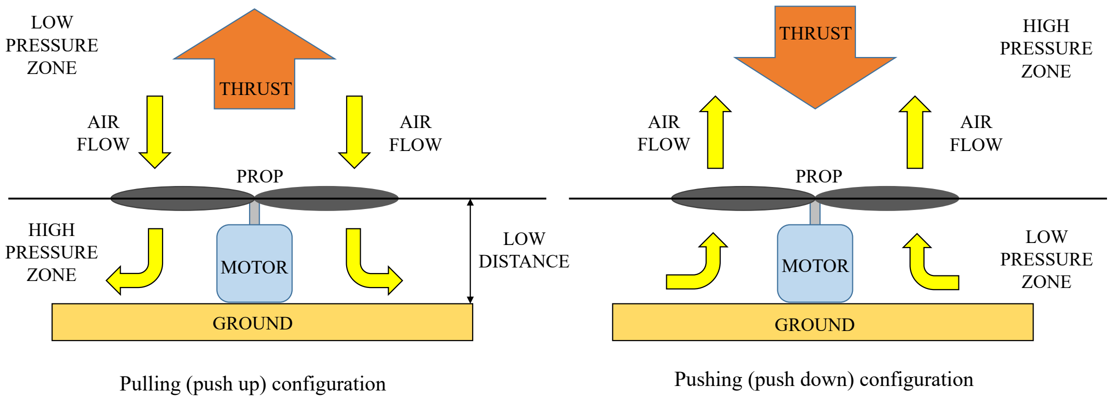


Figure 4.4: Pulling and pushing test configurations

4.3.4 Flight time computation

Since the nominal voltage is constant, the flight time of the drone can be computed by choosing a current value corresponding to a thrust that reproduces the hovering condition. The total weight of the drone is 250 g and consists of 4 engines. The hovering condition is obtained if each motor provides a thrust equal to:

$$T_{hov} = \frac{250}{4} = 62.5g \tag{4.1}$$

Taking into account the data obtained in the “push” configuration, this thrust value corresponds to current values equal to 1.2 A. This means that the total current absorber by the motors is:

$$I_{tot} = 4I = 4 \cdot 1.2 = 4.8 \tag{4.2}$$

Assuming to use a 1300 mhA 2S Lipo battery, the flight time is computed as follows:

$$FOT = \frac{battery\ capacity}{I_{tot}} = \frac{1.3}{4.8} = 0.27h = 16.25min \tag{4.3}$$

Which corresponds to a total power of:

$$P_{tot} = 4P = 4 \cdot 8.9 = 35.6 \tag{4.4}$$

By comparing the values with those provided by the eCalc Tool, the following results have been obtained:

Computed values		eCalc Tool values	
TOF [min]	Power [W]	TOF [min]	Power [W]
16.25	35.6	14.3	34.8

Table 4.3: Experimental data VS eCalc data

The variation of the calculated values compared to eCalc values is only 13.6% for the TOF and 2.3% for the power. It is therefore possible to consider the eCalc Tool quite reliable.

4.4 Varying V_N; 100% PWM

4.4.1 "Pulling thrust"

Imposing the throttle equal to 100%, mounting the propeller on the motor in order to obtain a traction effect (push up) and increasing the voltage step by step (starting from the minimum value of V which let the motor rotating), the following results have been obtained:

P_{IN} [W]	V [V]	I [A]	T_{start} [g]	T_{end} [g]	T_{real} [g]	T [N]	f_{el} [Hz]	f_m [Hz]	ω_m [RPM]	c_T
16,218	4,77	3,4	2147	2098	49	0,48069	972	162	9720	0,027718
20,007	5,13	3,9	2147	2092	55	0,53955	1038	173	10380	0,027281
31,959	6,03	5,3	2147	2081	66	0,64746	1145	190,8333	11450	0,026905

Table 4.4: Varying V_N, 100% PWM; pulling test measurements

4.4.2 "Pushing thrust"

The same operation has been repeated by coupling the propeller on the motor in order to have a pushing effect (push down). This was possible simply by reversing the coupling of the propeller and the direction of rotation of the motor. The following results have been obtained:

P_{IN} [W]	V [V]	I [A]	T_{start} [g]	T_{end} [g]	T_{real} [g]	T [N]	f_{el} [Hz]	f_m [Hz]	ω_m [RPM]	c_T
11,691	4,33	2,7	0	83	83	0,81423	920	153,3333	9200	0,052408
17,08	4,88	3,5	0	105	105	1,03005	1017	169,5	10170	0,054255
29,5	5,9	5	0	142	142	1,39302	1171	195,1667	11710	0,055344

Table 4.5: Varying V_N, 100% PWM; pushing test measurements

4.4.3 Pulling thrust VS pushing thrust

As can be seen from the following figures, also in this case, in the "pull" configuration, the same phenomenon described above has been detected: greater thrust and c_T in the "push" configuration at the same RMP value.

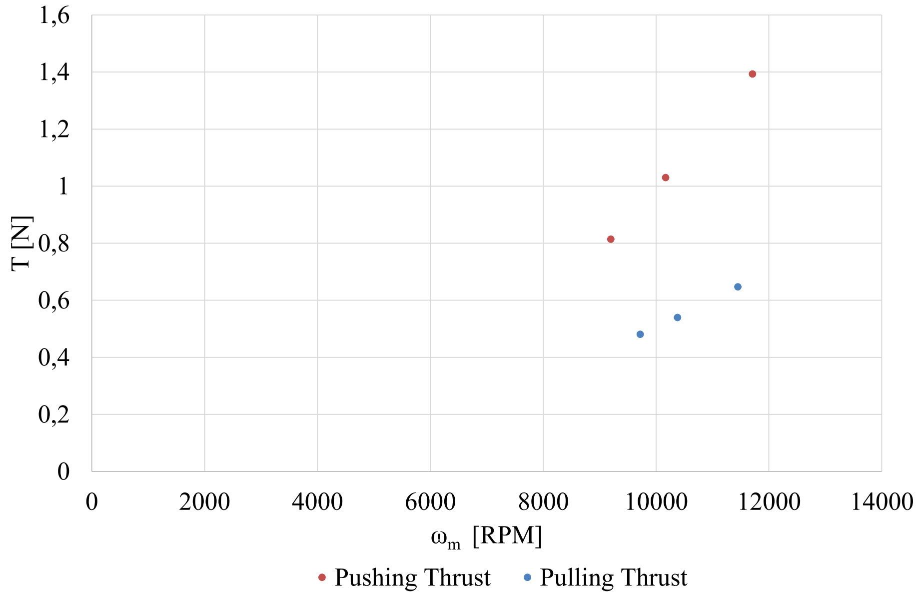


Figure 4.5: Thrust VS RPM (pushing VS pulling)

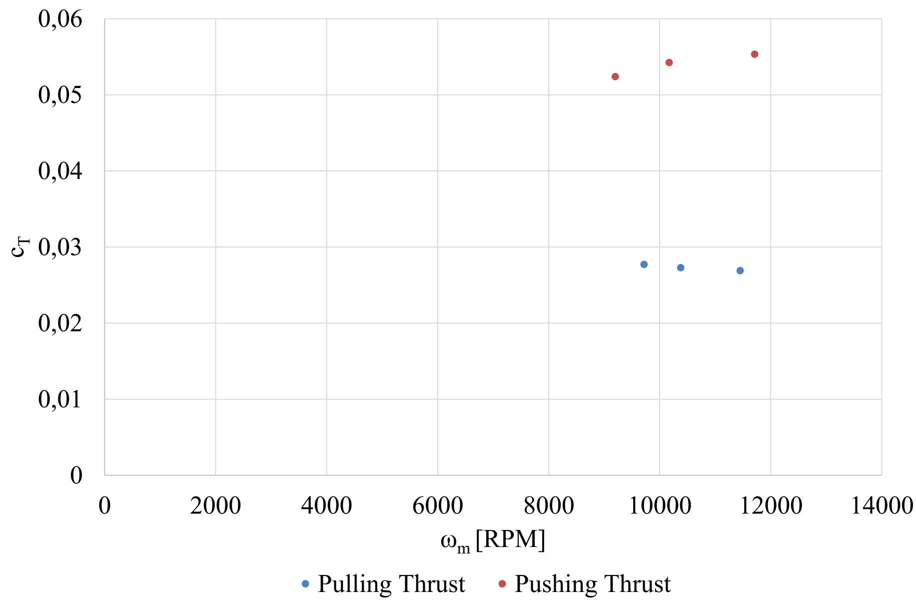


Figure 4.6: c_T VS RPM (pushing VS pulling)

4.4.4 KV computation

The system battery/ESC/PWM/motor/prop works as follow: The battery provide voltage and current (V_N and I_N) that are modulated by the ESC in order to supply the motor with the correct equivalent voltage and current (V_{eq} and I_{eq}). I_{eq} is always equal to I_N while V_{eq} ranges from 0 to V_N according to the PWM signal.

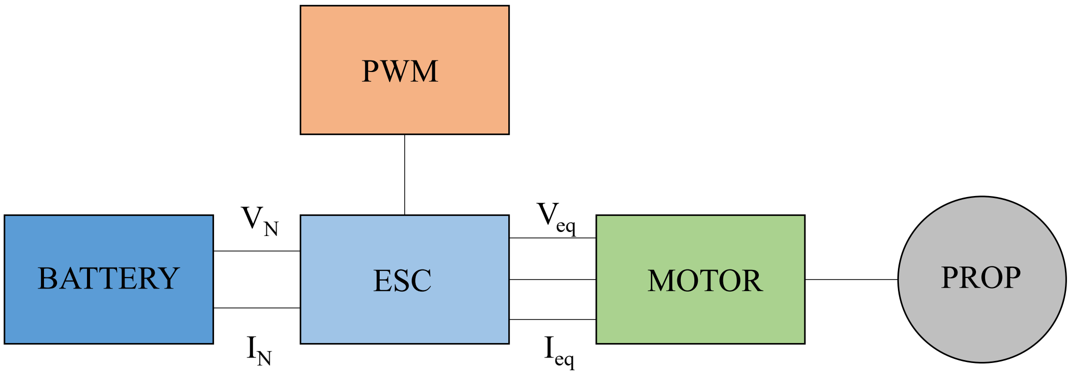


Figure 4.7: System scheme

Imposing a 100% throttle means that:

$$V_{eq} = V_N \tag{4.5}$$

And being the rotational speed of the motor equal to:

$$\omega = KV(V_{eq} - RI) \tag{4.6}$$

The KV values can be computed as follow:

$$KV = \frac{\omega}{(V_{eq} - RI)} \tag{4.7}$$

The internal resistance of the motor R is equal to 0.5 Ω and the KV factor can therefore be calculated for each values of current, voltage and angular velocity of the tables 4.4 and 4.5:

Pulling configuration			
V [V]	**I [A]**	$\omega_{\mathbf{m}}$ **[RPM]**	**KV**
4.77	3.4	9720	**3166.124**
5.13	3.9	10380	**3264.151**
6.03	6.3	11450	**3387.574**

Table 4.6: Pulling configuration; KV computation

Pushing configuration			
V [V]	**I [A]**	$\omega_{\mathbf{m}}$ **[RPM]**	**KV**
4.33	2.7	9200	**3087.248**
4.88	3.5	10170	**3249.201**
5.9	5	11710	**3444.118**

Table 4.7: Pushing configuration; KV computation

As shown in the tables 4.6 and 4.7, the KV values are around 3100 KV as stated by the manufacturer.

4.5 Considerations

The execution of this test made it possible to evaluate the performance of the Tmotor MT1306 and the Tmotor CF 6020 coupling obtaining the following results:

- The evaluation of the thrust by using the "pulling" (push up) configuration of motor and propellers is affected by an error due to the low distance between the propellers and the ground; therefore the best way to measure the thrust with this configuration is to use a structure that guarantees a wide escape route of the turbulent motion generated by the propeller. The pushing (push down) configuration is therefore preferable.
- The experimental data are comparable to those obtained from the analysis carried out by the Ecal tool. It is therefore possible to consider this tool useful for the purposes of this project.
- There are two versions of Tmotor MT1306; the first one, tested in this chapter, has an internal resistance of 0.5 Ω while the second, chosen for the construction of the drone, has an internal resistance of 0.06 Ω. By using the second version of the motor, the performances will increase significantly due to this great difference. In fact, the Ecalc tool give us a flight time equal to 21.9 minutes by using the version of the motor with the internal resistance equal to 0.06 Ω.

Chapter 5

Firmware and software

5.1 PX4 architectural overview

PX4 consists of two main layers: the flight stack and the middleware. The first is an estimation and flight control system while the second is a general level of robotics (it supports any type of autonomous robot) that provide internal and external communications and hardware integration[22].
PX4 uses the same code base for all types of vehicles (drones, airplanes, submarines, etc) and it is a reactive system. This means that:

- It uses interchangeable and reusable components that implement different functionalities.
- It communicates by synchronous messages passing.
- It can work with varying workloads.

5.1.1 High level software architecture

The main elements of the PX4 system are shown in figure 5.1: The various modules are connected by arrows that describe the main information flows and they use a named publish-subscribe message bus named uORB to communicates. This means that:

- The system is reactive and asynchronous and will update instantly when new data is available.
- All operations and communications are performed in parallel.
- Each component can process data in thread-safe mode.

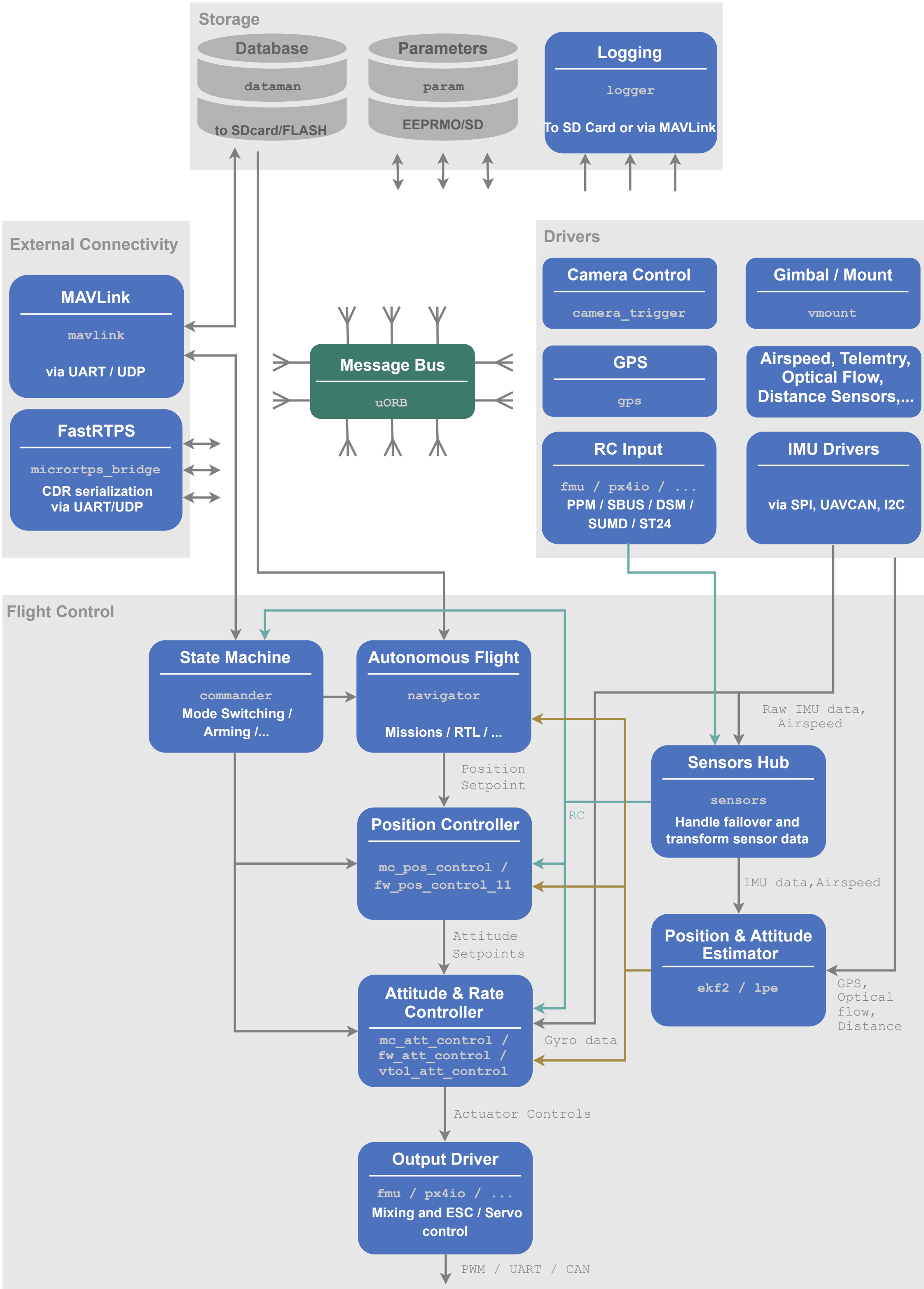


Figure 5.1: PX4 Architecture

5.1.2 Flight stack

The stack contains the set of flight control algorithms for autonomous driving drones such as fixed-wing, multi-rotor and VTOL aircraft. Figure 5.2 shows the flight stack control algorithm: the inputs from sensors, position and attidude estimator and RC are processed by the navigator, position controller and attitude and rate controller that control the motors.

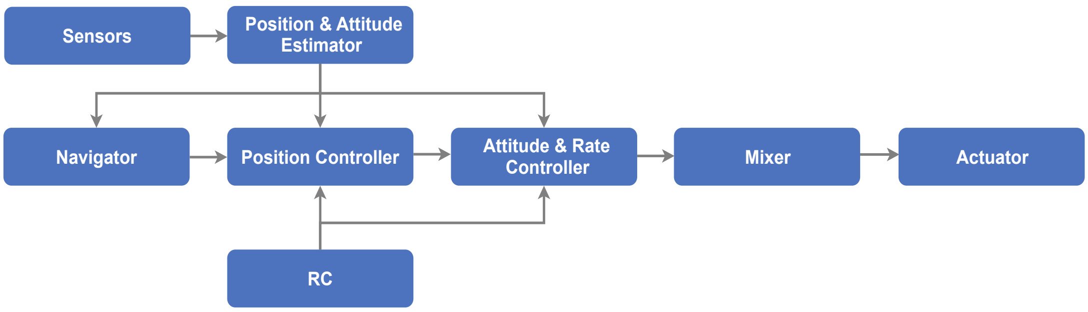


Figure 5.2: PX4 Flight stack

- The position and attitude estimator processes and combines the data received from the sensors and computes the status of the aircraft.
- The position controller receives a setpoint and a measurement or estimated state as input. Subsequently it regulates the process variables to make them coincide with the setpoint value. For example, the position controller acquires the position, estimates this value as a process variable, and returns a trim and push setpoint that moves the vehicle to the desired position.
- The mixer takes the commands and converts them into inputs for each motor (respecting the limits). This type of operation is necessary to ensure the correct relationship between factors such as input of the rotor with respect to the center of gravity and the inertia of rotation of the aircraft.

5.1.3 Middleware

The middleware is a driver that integrates the various sensors, communicates with the external environment and is responsible for managing the uORB subscription-publishing message bus.
It also allows to run PX4 firmware on a computer-modeled aircraft in order to perform virtual simulations on a desktop OS platform.

5.1.4 Update rates

Each module is waiting for a status update by message receiving. The update rate is defined by the drivers and for most IMUs it is 1kHz. This frequency is subsequently integrated at 250 Hz. Since some parts of the system such as the navigator do not need this high rate, they use a lower one.

5.1.5 Runtime environment

Any operating system that provides POSIX-API can execute PX4 firmware. The uORB asynchronous messaging API is based on shared memory so because the entire middleware is associated with a single address, all modules share the same memory space.
The modules can be executed in two different fashions:

- **Tasks:** the module performs its activity with its own stack and defines by itself the priority to be assigned to each process.
- **Work queues:** the module does not have its own stack and performs tasks in a shared manner. Therefore multiple activities are performed on the same stack and the priority for the work queue is unique.

A task is scheduled on a fixed schedule in the future. This allows to save RAM memory, but the task can not perform operations such as sleeping or polling on a message. Periodic tasks such as detecting the value of the sensors are then managed by work queues.

5.1.6 OS specific information

- **NuttX:** the main operating system on which the PX4 firmware is executed on a flight controller board is the NuttX RTOS. It holds a BSD (open source) license and is very light, efficient and reliable. Each module, which is executed as a task, holds its own file lists, shares an address space and runs one or more threads. All the stacks are controlled by a periodic task and each tasks and thread has a fixed size stack.
- **Linux/macOS:** on Linux or mac OS, PX4 is executed in a single process (modules are run in their own threads) and there is no distinction between tasks and threads like on NuttX.

5.1.7 Multicopter position controller algorithm

The following figure shows the position controller diagram of a multirotor running the PX4 firmware; it works as a standard cascaded position-velocity loop and the estimates are elaborated by a EKF2.
The position outer loop is bypassed according to the mode (it is shown as a multiplexer after the outer cycle). The position loop is used only during the hovering condition (position is maintained) or the speed in one direction is zero. In addition, the integrator inside the controller loop is equipped with an anti-reset windup through a clamping method.
The extended kalman filter algorithm is used to process sensor measurements and provide an estimation of the following states[23]:

- Quaternion defining the rotation from North, East, Down local earth frame to X,Y,Z body frame
- Velocity at the IMU - North,East,Down (m/s)
- Position at the IMU - North,East,Down (m)
- IMU delta angle bias estimates - X,Y,Z (rad)
- IMU delta angle bias estimates - X,Y,Z (rad)
- Earth Magnetic field components - North,East,Down (gauss)
- Vehicle body frame magnetic field bias - X,Y,Z (gauss)
- Wind velocity - North,East (m/s)

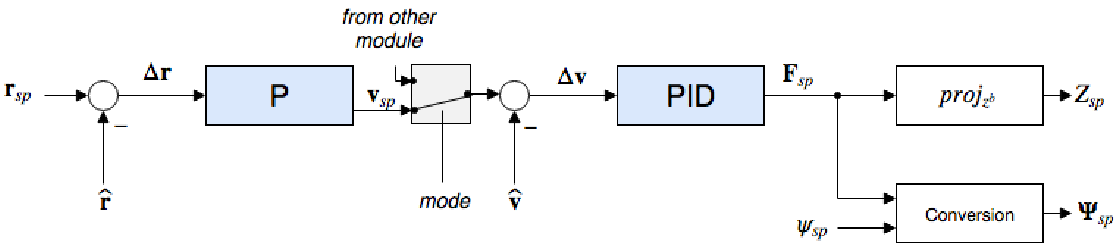


Figure 5.3: Multicopter position controller diagram

- r Position
- v Velocity
- Ψ Attitude
- F Thrust
- Z Body vertical thrust
- ψ Yaw angle
- Δ Difference
- $\widehat{(x)}$ Estimated value of x
- $(x)_{sp}$ Setpoint of x
- $proj_{z^b}$ Vector projected onto body Z-axes

5.2 Ground control station

As described in paragraph 2, an Unmanned Aircraft System is equipped with a ground control station. It is a software that runs on a computer, tablet or smartphone that communicates with the aircraft via wireless telemetry. It works as a “virtual cockpit” typical of a real plane and allows real-time data monitoring such as speed, altitude, position and route. Through this software it is also possible not only to directly control the drone by replacing the radio control but also to program specific missions according to the application to be performed [24].
There are several software of ground control stations but the most important are:

- **Mission Planner**
- **QGroundControl**

5.2.1 Mission Planner

Mission Planner is a ground control station that was initially created for the ArduPilot open source autopilot project. The software is not only able to control aircraft such as drones or aircraft but also vehicles such as rovers and submarines[25].
Mission Planner allows users to:

- Load the firmware into the autopilot board.
- Setup, configure, and tune th vehicle for optimum performance.
- Plan, save and load autonomous missions into the autopilot with simple point-and-click way-point entry on Google or other maps.
- Download and analyze mission logs created by your autopilot.
- Interface with a PC flight simulator to create a full hardware-in-the-loop UAV simulator.
- Monitor the vehicle's status while in operation.
- Record telemetry logs which contain much more information the the on-board autopilot logs.
- View and analyze the telemetry logs.
- Operate in FPV.

5.2.2 QGroundControl

QgroundControl allows users to configure flight controllers that run both ArduPilot or PX4 firmware. It is equipped with a simple and dedicated interface for beginners providing also advanced features for expert users [26].
The most important key features are:

- Full setup and configuration of ArduPilot and PX4 powered vehicles.
- Flight support for vehicles running PX4 and ArduPilot.
- Mission planning for autonomous flight.
- Flight map display showing vehicle position, flight track, waypoints and vehicle instruments.
- Video streaming with instrument display overlays.
- Support for managing multiple vehicles.
- QGC runs on Windows, OS X, Linux platforms, iOS and Android devices.

Figure 5.4: Mssion Planner interface

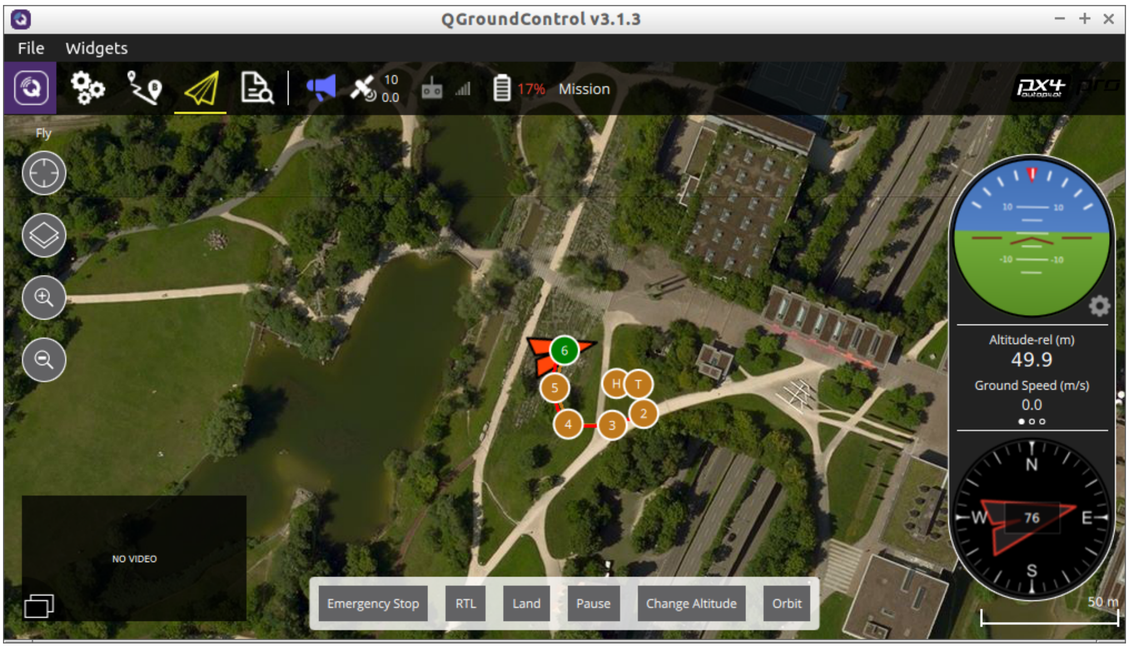


Figure 5.5: QGroundControl interface

Chapter 6

Troubleshootig

Once all the hardware components have been recovered it has been possible to start the assembly and testing phase of the aircraft. During these operations, a series of problems have been identified which will be described in this chapter together with the related solutions.

6.1 Assembly

6.1.1 Shopping list

The first problem concerns the shopping list; not all the components that have been described in the previous chapters have been traced on the market therefore it was necessary to replace some of them with equivalent devices. In particular:

- **Battery set:** the set of Thunderpower ® has been replaced with other batteries. In particular with:
  - Tattu ® Lipo 2S 800mAh 7.4V 45C (43 g)
  - Gens ® Lipo 2S 1300mAh 7.4V 25C (86 g)
  - Tattu ® Lipo 3S 850mAh 11.1V 75C (85 g)
- **GPS:** The Ublox ® SAM-M8Q GPS module which is definitely the best product for this project (very light) was not available so it has been decided to use the Ublox® SAM-M8Q GPS module included in the Pixracer starter kit. This solution involves an unexpected weight increase.

6.1.2 Components placement

The frame that has been described in the paragraph 3.4.5 is a 3 layers frame but 2 layers has been removed in order to reduce the mass of it. This means that in the single layer of the frame there are no suitable holes for fixing the components. For this reason it has been necessary to design an additional layer using Solidworks for the positioning of the components that have been fixed to the frame by means of rubber supports able to absorb the vibrations during the flight. This part has been made by 3d printing in PLA material. This solution involves a negligible weight increase.

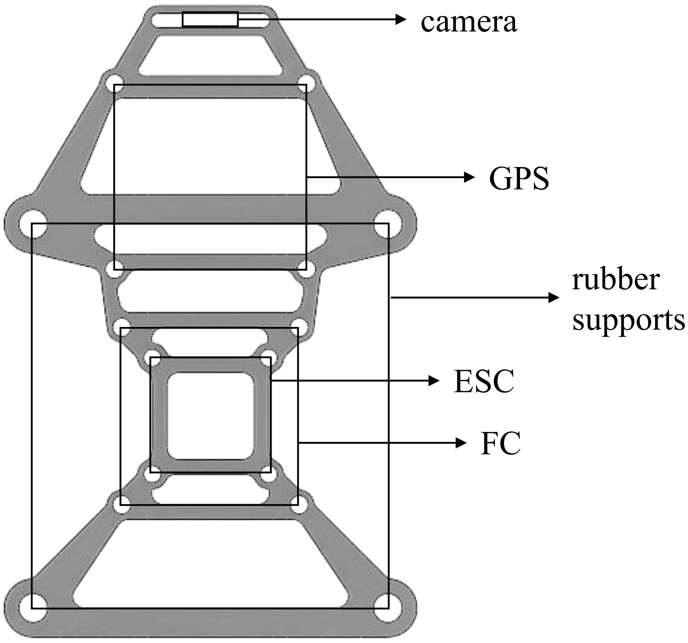


Figure 6.1: Frame support layer

6.2 Testing

Once all the components have been correctly positioned and assembled, the first tests have highlighted the following problems:

6.2.1 One motor in protection mode

At the first start of the drone, one of the four motor did not work properly and immediately entered in protection mode. The problem was the ESC that it could not properly control the motor for some reason; it has been enough to replace this component with a new one to solve the problem.

6.2.2 No signal from GPS

One of the main problems during the first tests was the absence of signals from the GPS that could not hook to any satellite. This problem has been solved by carrying out the so-called “cold start” using Ublox U-center software;
in general, a GPS module at the first start requires a prolonged time of exposure to hook up to the satellites in particular conditions (outdoors and in clear weather). After this

procedure the GPS module is ready to be used on any device to perform geolocation and navigation operations.
After the cold start, Qground Control showed an association with 9 satellites during the first test and the correct positioning of the device on the map.

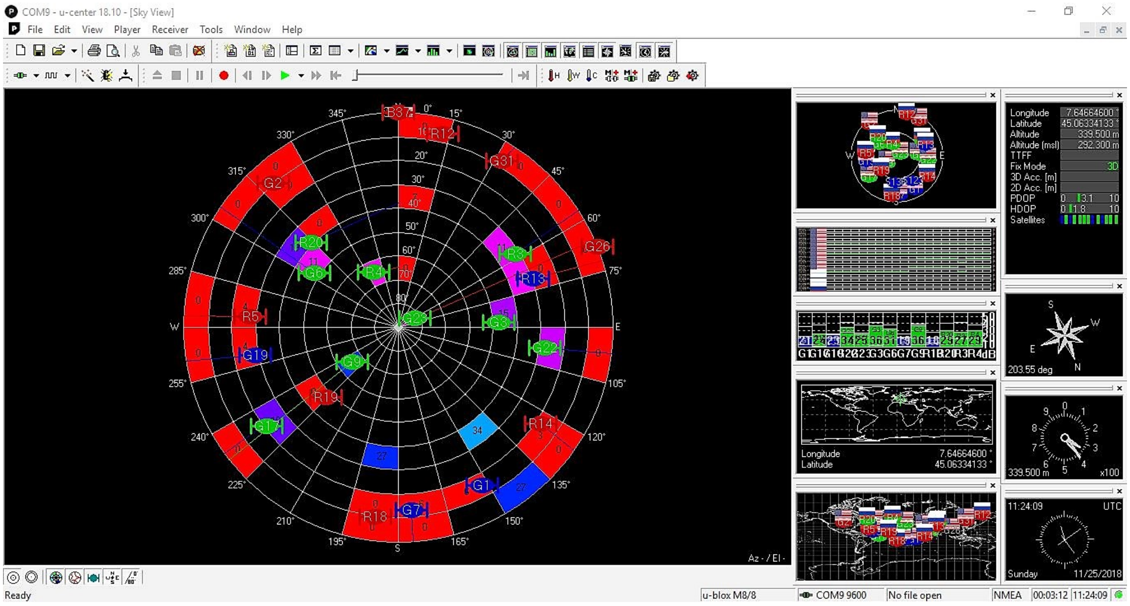


Figure 6.2: U-center interface during the cold start procedure

6.2.3 No binding between receiver and transmitter

An association between transmitter and receiver must be carried out in order to control the aircraft manually via radio transmitter; this procedure is called binding: both the receiver and the transmitter when they are in bindings mode are able to see each other and to associate correctly.
During this phase the FrSky x4r receiver which has been described in paragraph 3.4.3 did not enter in binding mode and was therefore not able to make itself visible to the transmitter. This problem has been solved by updating the receiver's firmware with the European version (the same as the transmitter). Indeed, the transmitter and receiver must necessarily have the same firmware version to be compatible with each other (typically there are two versions of EU and non-EU firmware).

Chapter 7

Conclusion

In the first part of this work the main characteristics of a UAV and the main sizing criteria of each single part have been described. Subsequently, the project of this thesis has been introduced by describing the design constraints and consequently the main objectives to be achieved. My approach has been to start from the firmware because thanks to the use of the PX4 firmware and its toolchain I have been able to respect most of the design constraints. 250 g is a very low value for a remotely piloted aircraf indeed the most difficult constraint to respect has been certainly that of weight. The objective has been nevertheless achieved thanks to the choice of the appropriate components, in particular the flight controller that allowed me to implement the telemetry by adding an ultralight module integrated to it and the motor/propellers coupling (T-motor MT1306 and T-motor CF 6020) that allowed me to have high performance while keeping the weight relatively low. The prototype must surely still be submitted to further evaluation tests, but it is possible to state that the main target of the project has therefore been achieved.

7.1 Final weight analysis

The weight analysis of the final prototype is shown in the table 7.1. As can be seen the total weight of the drone is 249 grams; just a gram under the limit imposed by the weight constraint.

Component	Model	Quantity	Weight [g]
FC	mRo Pixracer	1	10.54
Power Module	ACSP5	1	5
GPS	mRo GPS u-Blox Neo-M8N	1	20
Telemetry	Pixracer Wifi module	1	1
Motor	T- Motor MT-1306-10 3100 KV	4	44.8
Prop	T-motor 6020 Carbon Fiber	4	8.8
ESC	Lumenier Mini BLHeli 12A 4 in 1	1	20
Battery	TP870-2SE55J	1	49
Receiver	FrSky X4R-SB-3/16 Channel	1	5.8
Frame	Three Layer Frame Light Version	1	40.25
3D printed support layer	\	1	6
Payload	Runcam racer camera (5.5 g)	1	21
	ImmersionRC Tramp TX (4 g)	1	
	Triumph antenna (11.5 g)	1	
Cables, screws, rubbers and cabe ties	\	\	17.11
		MTOW	**249**

Table 7.1: Final weight analysis

7.2 TOF test

The FOT test have been executed by using the following 3 battery:

- Tattu ® Lipo 2S 800mAh 7.4V 45C
- Gens ® Lipo 2S 1300mAh 7.4V 25C

The following table shows the results that have been obtained during the tests and compares them with the theoretical values obtained through the formula 4.3 in section 4.3.4 according to the capacity of the battery under test:

	TOF [min]		
	Test value	**Computed value**	**Error**
2S 800 mAh	10	10	0 %
2S 1300 mAh	15	16.25	7.6 %

Table 7.2: TOF; test VS theoretical values

The results that have been obtained are exactly those expected for the 2S 800 mAh while a 7.6 % error is present for the 2S 1300 due to the overload in terms of weight. The 3S 850 mAh battery has not been tested but a TOF of around 11 minutes is expected.

7.3 Improvements

As described above, all the objectives have been achieved however the performances of the drone in terms of TOF can certainly increase. This can be done by performing a future state of the art of the individual components of the aircraft in order to choose the lightest and most performing ones. The components to work on are definitely the frame, the payload and the GPS module; by choosing lighter components would be possible to use a battery with greater capacity in order to increase the TOF.

Figure 7.1: Final prototype

Appendix A

Flight controllers specifications

Flight Controller	Specifications				
	Processor	**Sensors**	**Power**	**Interfaces Connectivity**	**Dimensions**
mRo Pixhawk	-32-bit STM32F427 Cortex® M4 core with FPU -168 MHz/256 KB RAM/2 MB Flash -32 bit STM32F103 failsafe co-processor	-ST Micro L3GD20 3-axis 16-bit gyroscope -ST Micro LSM303D 3-axis 14-bit accelerometer / magnetometer -Invensense® MPU 6000 3-axis accelerometer/gyroscope -MEAS MS5611 barometer	-Ideal diode controller with automatic failover -Servo rail high-power (7 V) and high-current ready -All peripheral outputs over-current protected, all inputs ESD protected	5x UART (serial ports), one high-power capable, 2x with HW flow control 2x CAN Spektrum DSM / DSM2 / DSM-X® Satellite compatible input up to DX8 (DX9 and above not supported) Futaba® S.BUS compatible input and output PPM sum signal RSSI (PWM or voltage) input I2C SPI 3.3 and 6.6V ADC inputs External microUSB port	-Weight: 38g -Width: 50mm -Thickness: 15.5mm -Length: 81.5mm
Pixhawk 2	-32bit STM32F427 Cortex M4 core with FPU -168 MHz / 252 MIPS -256 KB RAM -2 MB Flash (fully accessible) -32 bit STM32F103 failsafe co-processor	-Three redundant IMUs (accels, gyros and compass) -InvenSense MPU9250, ICM20948 and/or ICM20648 as first and third IMU (accel and gyro) -ST Micro L3GD20+LSM303D or InvenSense ICM2076xx as backup IMU (accel and gyro) -Two redundant MS5611 barometers	-Ideal diode controller with automatic failover -Servo rail high-power (max. 10V) and high-current (10A+) ready -All peripheral outputs over-current protected, all inputs ESD protected	-5x UART (serial ports), one high-power capable, 2x with HW flow control -2x CAN (one with internal 3.3V transceiver, one on expansion connector) -Spektrum DSM / DSM2 / DSM-X® Satellite compatible input -Futaba S.BUS® compatible input and output -PPM sum signal input -RSSI (PWM or voltage) input -I2C -SPI -3.3 and 6.6V ADC inputs -Internal microUSB port and external microUSB port extension	-Weight 75g -Width 43 mm -Height 31 mm -Length 94 mm

Flight Controller	Specifications				
	Processor	**Sensors**	**Power**	**Interfaces Connectivity**	**Dimensions**
Pixhawk mini	-Main Processor: STM32F427 Rev 3 -IO Processor: STM32F103	-Accel/Gyro/Mag: MPU9250 (deprecated by the PX4 firmware) -Accel/Gyro: ICM20608 Barometer: MS5611	-Power module output: 4.1~5.5V -Max input voltage: 45V (10S LiPo) -Max current sensing: 90A -USB Power Input: 4.1`5.5V -Servo Rail Input: 0~10V	1 x UART Serial Port (for GPS) -Spektrum DSM/DSM2/DSM-X® Satellite Compatible RC input -Futaba S BUS® Compatible RC input -PPM Sum Signal RC Input -I2C (for digital sensors) -CAN (for digital motor control with compatible controllers) -ADC (for analog sensors) -Micro USB Port	Weight: 15.8g Dimensions: 38x43x12mm
mRo Pixracer	-32-bit STM32F427 Cortex M4 core with FPU rev. 3 -168 MHz/256 KB RAM/2 MB Flash	-Invensense ICM-20608-G 3-axis accelerometer/gyroscope -Invensense MPU-9250 3-axis accelerometer/gyroscope/magnetometer -MEAS MS5611 barometer -Honeywell HMC5983 magnetometer temperature compensated	- Ultra low noise LDO voltage regulators	-5x UART (serial ports), one high-power capable, 2x with HW flow control and GPS+I2C® -CAN -Spektrum DSM / DSM2 / DSM-X® Satellite compatible input up to DX9 and above. -Futaba S.BUS® & S.BUS2® compatible input -FRSky Telemetry port output -Graupner SUMD -Yuneec ST24 -PPM sum input signal -OneShot PWM output (Configurable) -RSSI (PWM or voltage) input -I2C,SPI -External microUSB port -JTAG -Dronecode Debug connector -6x PWM outputs -JST-GH connectors using Dronecode connector standard	-Weight: 10.54g -Width: 36mm -Length: 36mm

Flight Controller	Specifications				
	Processor	**Sensors**	**Power**	**Interfaces Connectivity**	**Dimensions**
Pixhawk 4	-Main FMU Processor: STM32F765 32 Bit Arm® Cortex®-M7, 216MHz, 2MB memory, 512KB RAM -IO Processor: STM32F100 32 Bit Arm® Cortex®-M3, 24MHz, 8KB SRAM	-Accel/Gyro: ICM-20689 -Accel/Gyro: BMI055 -Magnetometer: IST8310 -Barometer: MS5611	-Power module output: 4.9~5.5V -USB Power Input: 4.75~5.25V -Servo Rail Input: 0~36V	-8-16 PWM outputs (8 from IO, 8 from FMU) -3 dedicated PWM/Capture inputs on FMU -Dedicated R/C input for CPPM -Dedicated R/C input for Spektrum / DSM and S.Bus with analog / PWM RSSI input -Dedicated S.Bus servo output -5 general purpose serial ports -3 I2C ports -4 SPI buses -Up to 2 CANBuses for dual CAN with serial ESC Analog inputs for voltage / current of 2 batteries	-Weight: 15.8g -Dimensions: 44x84x12mm
Pixhawk v5	-32-bit ARM Cortex M7 core with DPFPU -216 Mhz/512 KB RAM/2 MB Flash -32-bit co-processor	- InvenSense ICM20689 accelerometer / gyroscope -Bosch BMI055 accelerometer / gyroscope -MS5611 barometer -IST8310 magnetometer	-Operating power: 4.3~5.4V USB Input: 4.75~5.25V -High-power servo rail, up to 36V -Dual voltage and current monitor inputs	-6 IOMCU PWM servo outputs -8 FMU PWM outputs (D-Shot capable) -3 dedicated PWM/Capture inputs on FMU -S.Bus servo output -R/C inputs for CPPM, DSM and S.Bus -Analogue / PWM RSSI input -5x general purpose serial ports -4x I2C ports -4x SPI buses enabled -2x CAN Bus ports-6x PWM outputs	-Weight: 90g -Dimensions: 44mm x 84mm x 12mm

Flight Controller	Specifications				
	Processor	**Sensors**	**Power**	**Interfaces Connectivity**	**Dimensions**
Beagle Bone Blue	-1GHz ARM Cortex-A8 -2×32-bit 200-MHz programmable real-time units (PRUs) -512MB DDR3 RAM integrated -4GB 8-bit eMMC flash	-MPU9250 for accelerometers, gyroscope and internal compass (I2C) -BMP280 barometer	-Power module output: 4.9~5.5V -USB Power Input: 4.75~5.25V -Servo Rail Input: 0~36V	-Wifi (802.11bgn) -Bluetooth 4.1 and BLE -8x ESC/Servo out (6v), 4x DC motor out -USB 2.0 client and host -11x programmable LEDs -2x buttons -1.8V analog -SPI, I2C, UART -2-cell LiPo support with balancing, 9-18V charger input	-Weight 36g -175 x 112 x 40mm
Erle-Brain 3	-1.2GHz quad-core ARM Cortex-53 CPU, 1GB RAM, Broadcom VideoCore IV	-Gravity sensor -Gyroscope -Gigital compass -Pressure sensor and tempertature sensor -ADC for battery sensing	-LiPo battery and a Power Module connected through "Power" labeled connector. This method allows to get readings of the battery voltage. -standard 5v @2A microUSB charger.	-WiFi-enabled -ROS focus (Indigo available) -MAVProxy can automatically bridge MAVLink packets to your WiFi network. -Optional WiFi and Bluetooth. -Optional Camera: 8MP Fixed focus lens, 2592 x 1944 pixel static images, supports 1080p30, 720p60 and 640x480p60/90 video record -2x I2C, UART, Ethernet, 4x USB, PPM input -12 PWM output -Micro SD,Audio jack,HDMI,Micro USB	-Weight 100g -70 x 95 x 23.8mm

Flight Controller	Specifications				
	Processor	**Sensors**	**Power**	**Interfaces Connectivity**	**Dimensions**
F4BY FMU	-Single 32-bit ARM Cortex M4 core with FPU STM32 F407	-InvenSense MPU6000 IMU (accel, gyro) -MS5611 barometers -HMC5983 compass	-3x separate 3,3v LDO for CPU, Sensors, CAN -Servo rail backup power diode -reverse voltage and overvoltage power protection -board voltage and servo rail voltage sensors	-5x UART serial ports, 1 with inverter for frsky telemertry -Up to 12x PWM outputs -Spektrum DSM/DSM2/DSM-X Satellite input -Futaba S.BUS input support (with external inverter) -PPM sum signal -RSSI (PWM or voltage) input -I2C, SPI, CAN, USB -3.3V and 6.6V ADC inputs	-Weight 20g -50 x 50mm
OpenPilot Revo mini	STM32F405RG T6 ARM Cortex-M4 microcontroller -168 Mhz/1 MB Flash -32-bit failsafe co-processor	-InvenSense MPU6000 IMU (accel, gyro) -Honeywell HMC5883L compass -MS5611 barometers	-4.8V ~ 10V input power provided through ESC connection for fullsize Revolution -5V max on RevoMini	-6 PWM outputs -RC input PPM/sBus on RC input port's signal pin 3 (the yellow wire) -GPS rx / tx on Flexy port -Telem1 on mainport -USB port -SWD Port for flashing and debugging, including 3.3V output for optional periphereals -MMCX antenna connector for integrated HopeRF RFM22B 100mW 433MHz (fullsize Revolution only) -OPLink port.	-Weight 9 g -36x36 mm with 30,5x30,5 mm hole spacing

Flight Controller	Specifications				
	Processor	**Sensors**	**Power**	**Interfaces Connectivity**	**Dimensions**
PXF mini	-Raspberry Pi zero needed	-3 axes gravity sensors -3 axes gyroscope -3 axes digital compass -Pressure sensor -Temperature sensor -ACS for battery sensing	-USB input -Power module input -Servo rail input	-Pre-configured to create an WiFi hotspot in the 5GHz bandwidth, in order to be able of using together 2.4GHz RC and WiFi -MicroSD -HDMI -8 channel of PWM output (Each channel has 25 mA current sink capability at 5V) -RC Input -Connectors complying with the Dronecode Autopilot Connector Standard -Two I2C bus connectors, which gives access to the I2C bus -Telemetry	-Weight 15g -31 x 73 x 8.9 mm
TauLabs Sparky2	-STM32F405 ARM Cortex-M4 microcontroller -168 Mhz/1 MB Flash -32-bit failsafe co-processor	-InvenSense MPU9250 IMU (accel, gyro, compass) -MS5611 barometers -Dataflash for logging	-4.8V ~ 10V input power provided through ESC connection	-6x PWM outputs (+4 more on LED port) -1x RC input PWM/PPM -2x analog to digital inputs for battery voltage and current monitoring -1x serial input for GPS -1x I2C port for external compass -1x CAN bus -MMCX antenna connector for integrated radio -USB port -SWD Port for flashing and debugging	-Weight 13.5 g -36x36 mm

Bibliography

[1] Futurism.com, *Benefits of drones*, https://futurism.com/images/benefitsofdrones

[2] Pierluigi Marzo, *Design and Integration of a Lightweight UAV for Critical Applications*, (Oct. 2017).

[3] Wikipedia , *European Aviation Safety Agency*, https://en.wikipedia.org/wiki/European_Aviation_Safety_Agency

[4] Droni-inoffensivi.it, *Droni sotto i 250 grammi liberi dall'obbligo di registrazione: quando si farà?*, https://www.droni-inoffensivi.it/droni-sotto-i-250-grammi-liberi-obbligo-di-registrazione/

[5] Oscarliang.com, *Choosing Quadcopter Components*, https://oscarliang.com/quadcopter-hardware-overview/

[6] Droneomega.com, *How GPS Drone Navigation Works*, https://www.droneomega.com/gps-drone-navigation-works/

[7] Oscarliang.com, *How to choose motor for racing drone quadcopter*, https://oscarliang.com/quadcopter-motor-propeller/#quadcopter-weight-motor-thrust

[8] Oscarliang.com, *How to choose propeller for mini quad*, https://oscarliang.com/choose-propellers-mini-quad/#directions

[9] Oscarliang.com, *How to choose ESC for racing drones and quadcopter*, https://oscarliang.com/choose-esc-racing-drones/

[10] Dronetrest.com, *How to choose the right motor for your multicopter drone*, https://www.dronetrest.com/t/how-to-choose-the-right-motor-for-your-multicopter-drone/568

[11] Dronetrest.com, *Beginners guide to drone autopilots (flight controllers) and how they work*, https://www.dronetrest.com/t/beginners-guide-to-drone-autopilots-flight-controllers-and-how-they-work/1380

[12] Getfpv.com, *All About Multirotor Drone Radio Transmitters and Receivers*, https://www.getfpv.com/learn/new-to-fpv/all-about-multirotor-fpv-drone-radio-transmitter-and-receiver/

[13] Oscarliang.com, *How to chosse LiPo battery for mini quad, drones and quadcpters*, https://oscarliang.com/lipo-battery-guide/

[14] Dronetrest.com, *LiPo Batteries - How to choose the best battery for your drone*, https://www.dronetrest.com/t/lipo-batteries-how-to-choose-the-best-battery-for-your-drone/1277

[15] Wikipedia, *Autopilot*, https://en.wikipedia.org/wiki/Autopilot
[16] Wikipedia, *MAVLink*, https://en.wikipedia.org/wiki/MAVLink
[17] Ros.org, *Documentation*, http://wiki.ros.org/
[18] Ros.org, *Mavros*, http://wiki.ros.org/mavros#Overview
[19] Ardupilot.org, *Software*, http://ardupilot.org/about
[20] Wikipedia, *PX4 autopilot*, https://en.wikipedia.org/wiki/PX4_autopilot
[21] Ecalc.ch, *XcopterCalc*, https://www.ecalc.ch/xcoptercalc.php
[22] Dev.px4.io, *PX4 Architectural Overview*, http://dev.px4.io/en/concept/architecture.html
[23] Dev.px4.io, *Using the ecl EKF*, https://dev.px4.io/en/tutorials/tuning_the_ecl_ekf.html
[24] Ardupilot.org, *Choosing a Ground Station*, http://ardupilot.org/copter/docs/common-choosing-a-ground-station.html
[25] Ardupilot.org, *Mission Planner Overview*, http://ardupilot.org/planner/docs/mission-planner-overview.html
[26] docs.qgroundcontrol.com, *QGroundControl User Guide*, https://docs.qgroundcontrol.com/en/