Ecole Nationale Supérieure d'Informatique

et d'Analyse des Systèmes

Rapport de Stage de Fin de 2ème Année

Option

Ingénierie des Systèmes Embarqués et Mobiles (ISEM)

Sujet

Développement d'un Véhicule multi-missions de type UAV (drone)

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Année Universitaire 2016-2017

Abstract

This document is the summary of the work I did on this year's internship project, under the supervision of Mr. Ismail AIT MELLAL.

The purpose of this project is to establish a system of drones able to fly synchronously and communicate with each other to intervene for example in rescue missions, transport, scientific research, and civil use…

A large project like this required meticulous planning and a wide range of technical skills; therefore, we have been 2 pairs working on it.

To achieve this, we started by defining a scope and evaluating the idea of the project, then we structured it by breaking it down into manageable parts, and then we started the implementation steps that we established and concluded with the project. edition of this report.

Key words: System, Drone, Synchronization, Communication

Acknowledgements

I would like to take the opportunity to thank:

ENSIAS, My school for giving us the opportunity to foster our level and helping us to acquire a pretty rewarding experience.

INTELCAPP Company for giving me the chance to work on this project. I have received a lot of knowledge and expertise and would especially like to thank **Mme.Housna ILALI** and **Mr.Ismail AIT MELLAL** for their enormously appreciated support.

The jury members that i’am honored by their presence and their acceptance to evaluate and appreciate our project.

My parents for their love, support through difficult situations and sacrifices.

All of my friends in ENSIAS.

Everyone who has contributed from near or far in the accomplishment of this project.

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Introduction

The end-of-year project is a crucial step in the ENSIAS curriculum, even more so for Embedded Systems' students. It has the added value of presenting an opportunity to comprehend the engineering activity in both its technical and managerial aspects.

With emerging commercial and governmental applications for disaster relief, pollution remediation, public safety and agricultural efficiency, the industry of drones has the potential to completely transform the way we live and work.

Our project revolves around creating a system of interconnected drones aiming to fulfill various missions, guaranteeing public safety to name one.

This report retraces the work we've carried out in this project, and it is structured into the following chapters:

The first chapter defines the general context of the project and its problematics. It is a generic entry describing our overall vision and detailing our planning of the activity of the team members.

The second chapter will mark the start of the theoretical and technical aspects of the project. It will detail the materials used to construct the drones along its flight principles.

In the third chapter, we'll proceed to a study of the dynamics of our system through mechanical equations.

In the fourth chapter, we'll harp on the stabilization and control of the drone. We will introduce a model of the drone with MATLAB Simulink, with the aim of stabilizing it using PID.

The fifth chapter is articulated around drones' inter-communication. In it, well discuss the two communication process XBee and GSM, and we will choose the more appropriate one for our system.

Last but not least, we'll move on to discussing the camera feature in our drone before concluding this report.

Chapter I: General context of the project

1. host organization

1.1 General presentation

INTELLCAP is a Moroccan company created in 2008 at the initiative of Mr. ILALI Idriss. INTELLCAP, specialized in training, research, development and technological innovation, among others, in the fields of renewable energies and water, offering integrated and on-demand solutions for businesses and organizations. She says she has the expertise to do her job professionally. INTELLCAP operates in several fields of activity:

- Aeronautics, Aerospace, Renewables, electric vehicles, production and prototyping ...
- R&D, the technological development of innovative solutions through the realization of Turnkey technological systems developed to integrate the country in the era of industrialization.
- La formation des jeunes et leur accompagnement dans la création de startups innovantes sur la base de technologies nationales.

In addition, for each domain:

Research and Development: INTELLCAP has forged partnerships with Al Akhawayne University In Ifrane (AUI), IRESEN, and other agencies and design offices to develop innovative solutions in the field of electric vehicles, storage and production of clean energy, aeronautics.

Technology & Engineering: INTELLCAP has forged partnerships with organizations and consulting firms to develop innovative vehicle solutions electrical, storage systems and clean energy production, aeronautics.

Education & Training: Education Through the Apprenticeship Process convenient. INTELLCAP has developed in several partnerships, the concept and the practice pelagic workshops that aim to introduce young people to school and not educated to industrial and technological techniques respectful of the environment.

Services: These consist of offering legal and financial advice, scientific industrial and technological development by supporting STRATUPS in their assembly the financial and legal phase up to the creation and implementation phase of their development.

1.2 organization chart of INTELLCAP

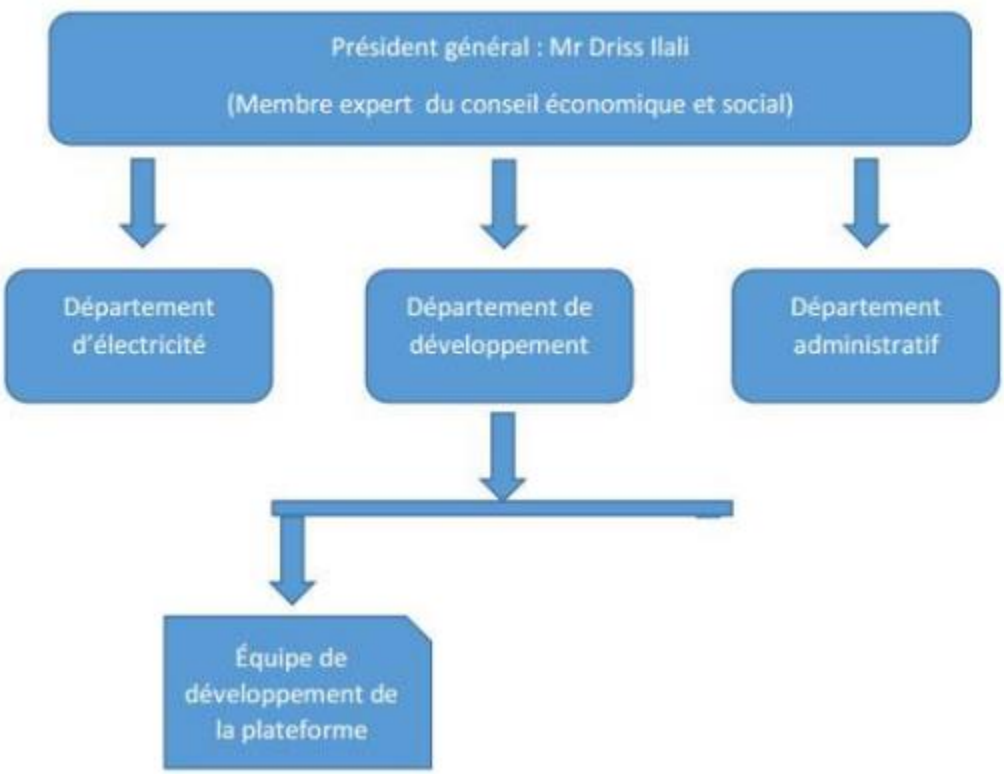
INTELLCAP is a company under Moroccan law, characterized by a vertical organization or the hierarchical character is not omnipresent. It consists of several organs:

Management and general presidency: The body of stewardship

Department of Development: The body that is made up of employees (engineers, technicians, assistants ...). The team includes Moroccans as well as foreigners, who intervene on a case-by-case basis and their intervention is generally distance or nearby depending on the situation. We were part of this department, and more precisely the platform development team.

Electricity Department: This body includes the various employees who work on embedded systems projects.

Administrative Department: This body comprises the different employees of the resources as well as the Secretary General of Intellcap.



Decision-making is done in a collegial manner in consultation with all membersof the INTELLCAP team.

The functioning of the company is governed by an internal regulation and a quality manual and of procedures that is updated as needed.

2. Project description

Before moving to addressing the technicalities of this project, we'll start with the basics by defining what constitutes a drone. Broadly, it is a vehicle designed for flight that does not have a pilot on board and is instead controlled remotely.

We can easily see how wide the spectrum of drones' applications is. In fact, they are already being used to deliver medicine to remote areas, monitor crops, inspect electric and gas facilities, and aerially photograph real estate and so on.

For our project, we chose to work with a particular kind of drones which is quadcopters.

A quadcopter has four arms with a motor and propeller on the end of each arm. In the typical configuration the rotors are arranged with two rotors turning clockwise and two rotors turning counter-clockwise.

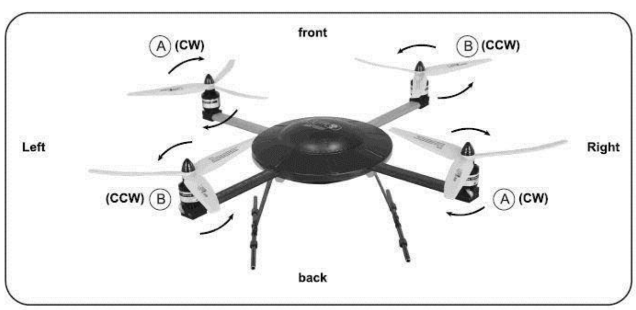


Figure 1: Quadcopter

A quadcopter can achieve vertical flight in a stable manner and be used to monitor or collect data in a specific region. Technological advances have reduced the cost and increased the performance of the low power microcontrollers, which allowed the general public to develop their own quadcopters.

The goal of this project is to build, modify, and improve an existing quadcopter kit to obtain stable flight, and communicate with other drones.

The project used an Aeroquad quadcopter kit that included a frame, motors, electronic speed controllers, Arduino Mega development board and sensor boards used with the provided Aeroquad software. Batteries, a transmitter, a receiver, a Bluetooth module, and a micro SD card adaptor were interfaced with the kit.

The aeroquad software was modified to properly interface the components with the quadcopter kit. Individual components were tested and verified to work properly. Calibration and tuning of the PID controller was done to obtain proper stabilization on each axis using custom PID test benches. Currently, the quadcopter can properly stabilize itself, determine its GPS location, and store and log data. Most of the goals in this project have been achieved, resulting in a stable and maneuverable quadcopter.

3. Specifications

3.1. General specifications

1- The system is launched in the zone where one wants to carry out the rescue at sea.

2- The system allows a self-inflating buoy to be placed near a person who is in difficulty.

3- Thanks to its high-quality video, the system offers remote recognition and control of the victim's condition.

4- The system communicates victim status information to another system.

5- The drone specifies the exact coordinates of the victim

6- Thanks to the information sent by the system, we can go directly to the victim and save him.

3.2. Detailed specifications

1- The drone takes off in the zone where one wants to carry out the rescue and uses some sensors

- ➢ Gyroscope
- ➢ Bluetooth sensor

2- The system can take video or photos

- ➢ Camera / raspberry

3- The system communicate many information about victim’s conditions

- ➢ GSM communication: GSM shield / Arduino card
- ➢ Communication by zigbee: XBee shield / Arduino card

4- The system can be manually controlled by a remote control

3.3. Functional requirements

4. Wireless communication with Bluetooth sensor HC-05.
5. The microcontroller used is the Atmega328
6. The IMU used is 9d0f razor
7. The programming software used is ARDUINO IDE.
8. Model-Based Design and simulations software is Matlab/Simulink
9. The energy is delivered by a rechargeable battery.
10. The system aim is to facilitate rescue and castaway detection

3.4 Non-functional requirements

1- Availability: The system must work and be able to provide its services.

2- Reliability: The system must provide proper functionality, as expected by users.

3- Safety: The system should be nothing very undesirable (causing damage to people,)

4- Security: The system must withstand intruders

5- Transparency: The system must operate in an easy way for the administrator to see what actions are performed.

Chapter II: Material and methods

The quadcopter is a flying machine equipped with four rotors placed at the ends of a cross. It is these four rotors which provide the vertical force (lift) which allows the apparatus to rise. In flight, the four-rotor can evolve according to its yaw, pitch and roll axes as well as in translation in all the directions. Also, such a machine is completely unstable and to control, it is necessary to develop a system that controls the engine power individually to counter the inclination of the different axes. It is the achievement of this stabilization system that is discussed in this report.

1. Methods

1.1. Movements of the drone

In this chapter we will describe the system, its general structure and the principle of flight.

It is essential to understand the movements of the drone, in order to be able to model it and to be able to stabilize it. It is also very important to ensure that the simulations of the behavior of the system are very close to reality.

The purpose of this chapter is to establish dynamic equations.

The quadrirotor is considered to be a very complex flying system.

Its dynamics are affected by several physical effects: aerodynamic effects, gravity, gyroscopic effects, friction and moment of inertia.

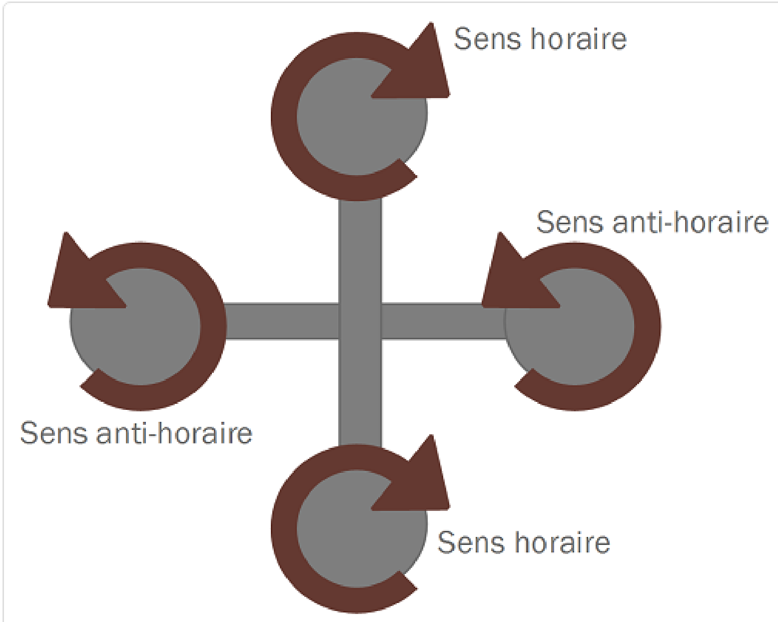


Figure 3: Movement of the drone

A quadrotor is a kind of "helicopter" with 4 propeller arranged on the same plane (parallel to the horizon in stability).

The system moves in three dimensions, rotating around three axes:

- ❖ The roll axis
- ❖ The pitch axis
- ❖ The Yaw axis

1.2. Direction of rotation and possible movements

A quadrirotor has, as the name suggests, four rotors to sustain. To counteract a yaw moment, it is necessary to rotate two propellers in one direction and the other two in the other direction. Indeed, when the aerodynamic forces are projected Exerted by the air on the blade, it can be seen that a rotor always tends to rotate the quadrirotor in the opposite direction to its rotation.

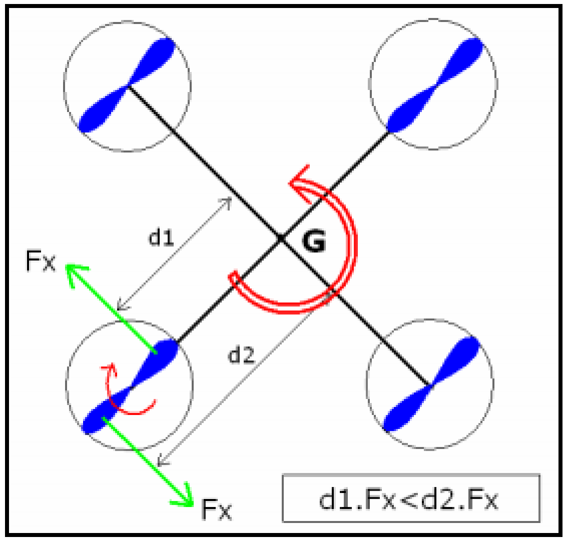


Figure 4: Moment de lacet

In addition, to facilitate the management of the pitch and roll controls, one chooses the front of the quad rotor at a rotor (and not between two rotors) and engines that are face to face in the same direction.

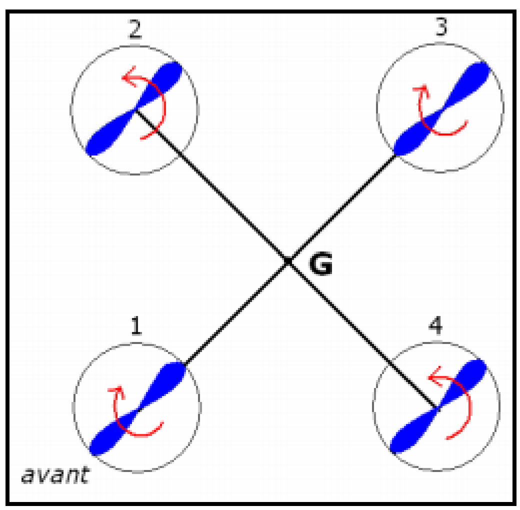


Figure 5: Motors' sense of rotation

Thus, the controls of the four engines will be used to change the acceleration vertical (power control) and to rotate the quad rotor around the vertical axis (Yaw command).

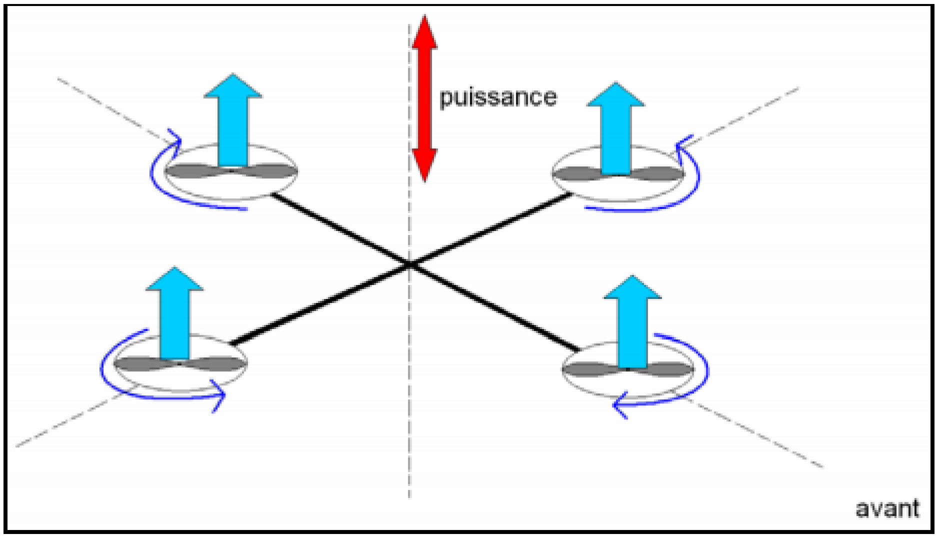


Figure 6: Commande de puissance

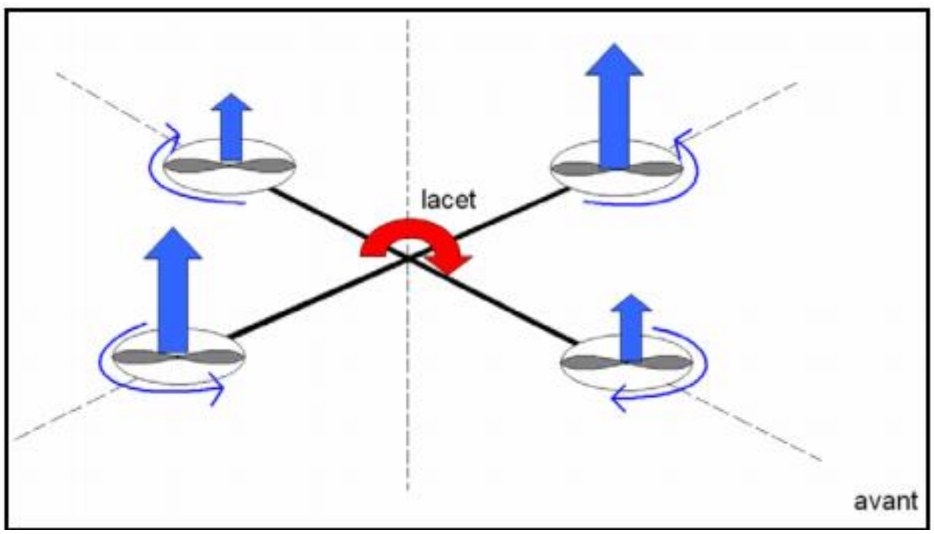


Figure 7: Commande de lacet

Only the controls of two opposing motors allow rotation around the longitudinal axis (roll control). In the same way, the commands of the two other motors allow rotation around the lateral axis (pitch control).

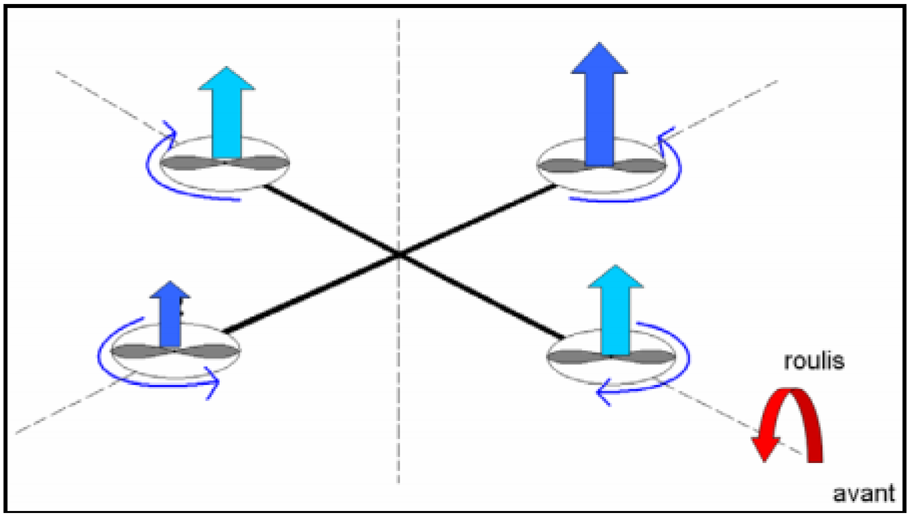


Figure 8: Commande de roulis

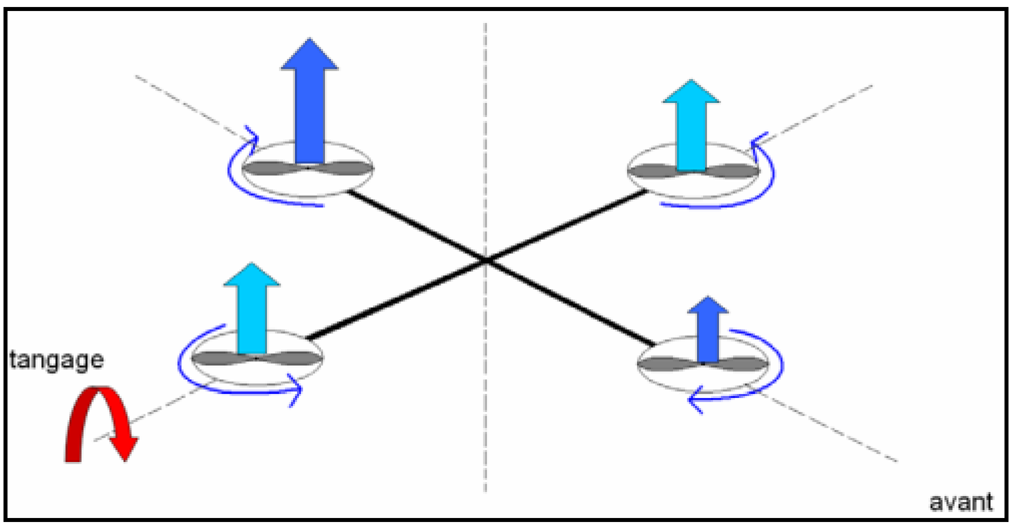


Figure 9: Commande de tangage

1.3. The attitude of the drone

To raise the drone, simply accelerate all the propellers, and vice versa for the descent.

To make it go left and right (or forward and backward), it is enough to accelerate the propeller being in the direction opposite to that which one wishes to borrow.

The propeller will then rise, and the drone will be bent. It will naturally turn in the desired direction.

Finally, it is possible to turn it on itself. For this purpose, it is necessary to accelerate two propellers which are not side by side but opposite to one another.

In order to understand this, let us take a closer look at the role of each propeller.

If we turn the four propellers in the same direction, then the drone naturally turns on itself.

In order to counteract this movement called the yaw movement, we rotate in the same direction two propellers lying opposite each other, and in the other direction the two remaining ones.

Now, if we accelerate two propellers turning in the same direction without touching the other two, the quadrirotor starts to turn on itself. It is thus possible to control its yaw movement and to orient the drone as desired.

To control the rotation about the yaw axis, two propellers must rotate clockwise, and the other two must rotate counterclockwise.

It is also necessary that the propellers rotating in the same direction are opposite to each other.

To rotate the device (around the yaw axis) and apply an inertial force, we will have to apply a speed differential between the pair of propellers rotating in one direction and the pair rotating in the other.

To rotate the machine (around the roll / pitch axis), a differential speed of the opposing motors (to tilt them one way or the other) must be applied.

1.4. Control

On a quadrotor, all motors are controlled according to the values of the 4 controls (gas, yaw, roll and pitch).

This means that a stage for converting the setpoints into motor drives has to be done.

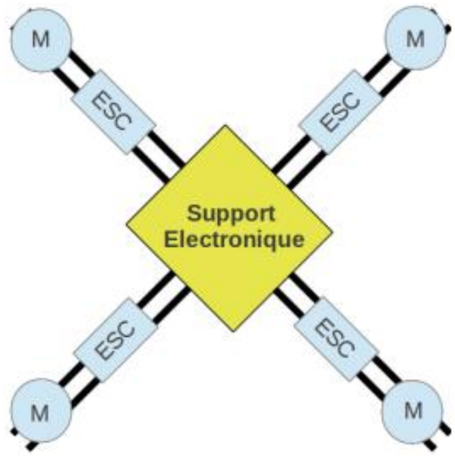


Figure 10: Drone's architecture

2. Materials

2.1. Used material

- Simple propellers, plastic, 20cm :

Figure 11: Simple propellers

➢ Brushless motor:

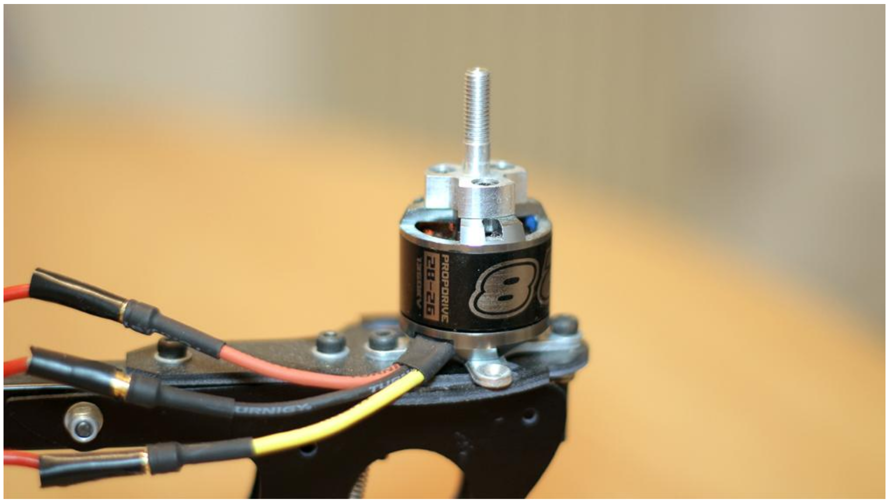


Figure 12: Brushless motor

➢ "Li-Po" 1300mAh, 3S (11.1V), 45-90C batteries (Capable of providing between 58.5 and 117 amps):

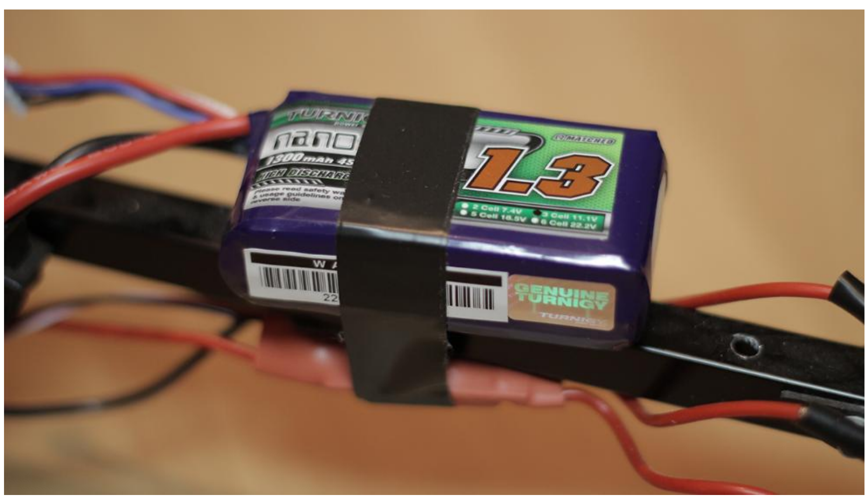


Figure 13: Li-Po

- Speed controllers (or ESC) :

Variable speed drives are what will make it possible to vary the speed of our engines, and therefore of our propellers. It is not enough to change the DC voltage at the terminals of a brushless motor to vary its speed, unlike a standard DC motor.

Moreover, the power supply to the motors is three-phase (three-wire). There are speed controllers for brushless motors, which can be controlled by a control signal.

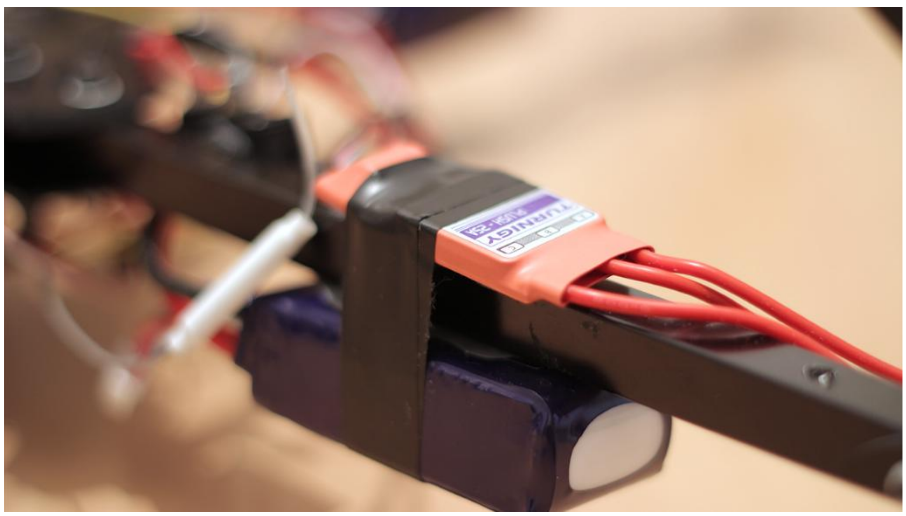


Figure 14: Speed Controllers

- The microcontroller :

Obviously, the most important thing is a microcontroller. In order to control the drone, to stabilize it, we will have to inject a kind of intelligence, program it. Before the construction of the drone, we had an Arduino Mega 2560. It is a very popular circuit board, and includes an Atmel AVR microcontroller.

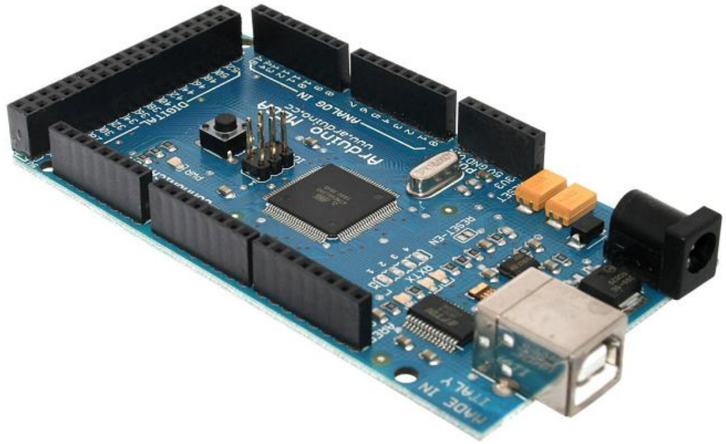


Figure 15: Microcontroller

2.2. Choice of : Engines/ESCs/Batteries

2.2.1. Choice of engines

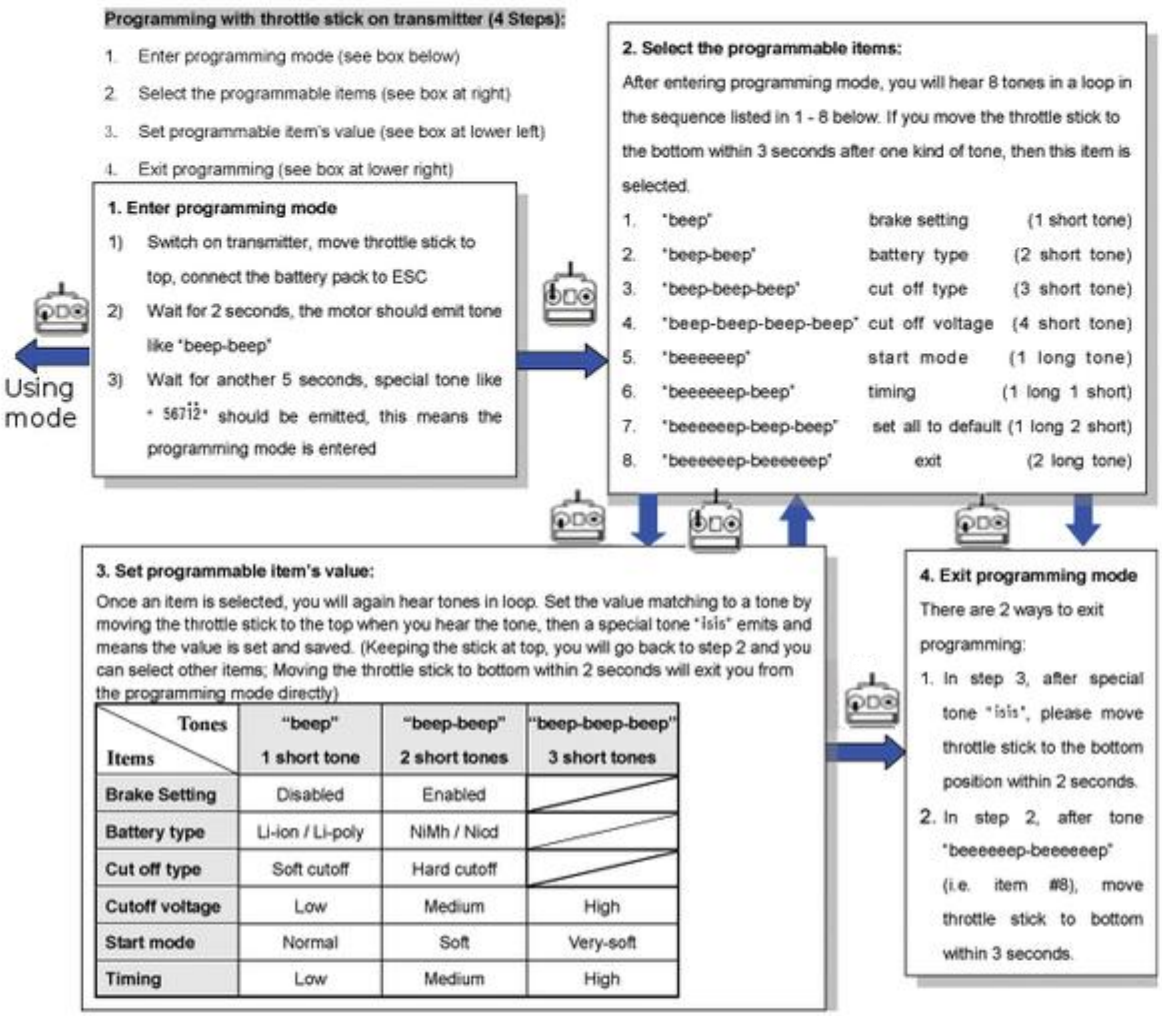
On the reference of the motors it is specified the type of propeller that can have use with this engine. Again this choice depends on what one wants to do: speed, reactivity, stability, autonomy, couple, cut the merguez, mount the whites in snow, etc.

2.2.2. Choice of ESCs

The choice of ESCs stems directly from that of the engines. Indeed, it is enough to look at the max current and the voltage consumed by the engine to choose an ESC. The engines we chose are in 11.1v and consume 15.5 A max. Thus, we chose ESCs of 25A (it is always better a margin).

2.2.3. Programming of ESCs

Now it is necessary tp program the ESC (because there are options). On the radio control it is simple, it is enough to carry out the following manipulations (in mode 2):



Tones / Items	"beep" 1 short tone	"beep-beep" 2 short tones	"beep-beep-beep" 3 short tones
Brake Setting	Disabled	Enabled	
Battery type	Li-ion / Li-poly	NiMh / Nicd	
Cut off type	Soft cutoff	Hard cutoff	
Cutoff voltage	Low	Medium	High
Start mode	Normal	Soft	Very-soft
Timing	Low	Medium	High

Figure 16: Programming of ESCs

2.3. Balance of power

2.3.1. *Study the LIPO batteries and its properties*

Figure 17: LIPO Batteries

- Each battery consists of several cells that will define the voltage delivered by the batteries.
- The voltage delivered by a single cell is 1s=4volts,therefore fore 2 cells 2s=8volts,for 3 cells 3s=12volts .....
- The voltage of each acc(cell) should never exceed 3 volts , means that the minimum voltage per cell will be 3 volts, and if it is greater than 3 volts it may damage the battery.
- Discharge/Discharge<C> :

  -The C value is the maximum capacity for discharging the battery , that's mean, we can dischagre the battery at a power up to nC the capacity of the battery continously.

-To avoid damaging the battery, it should always be charged at a value of 1C.For example, a 2200mAmp/h battery should not be charged more than 2.2Amp.

-Discharging to a value greater than the capacity will damage this battery.

-For proper operation,keep a charge of minumum 20% after each use.

2.3.2. ESC (electronic speed controller)

Its functionality is used to control the motor rotation speed according to our radio control.

Figure 18: ESC

- The BEC (battery eliminator circuit) is the part of the speed controller, it supplies power to the receiver and the servos, at the beginning of the electronic planes. They used a battery to power the motor and another battery to power the receiver, that's product the need of battery to power the receiver. But BEC use one battery and with two function, and it eliminates the need to battery which gives the power to receiver.
- BF 20Amp is the maximum current allowed by this controller to power the motor (in our ESC we find BF 20Amp).

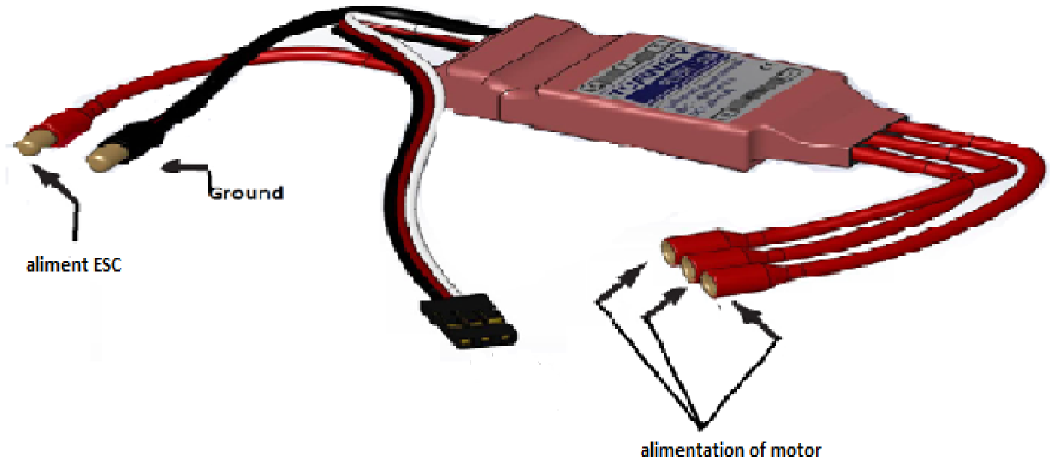


Figure 19: BEC/BF

The inputs of ESC

It contains about 2 cables linked to the battery and a cable linked to the receiver.

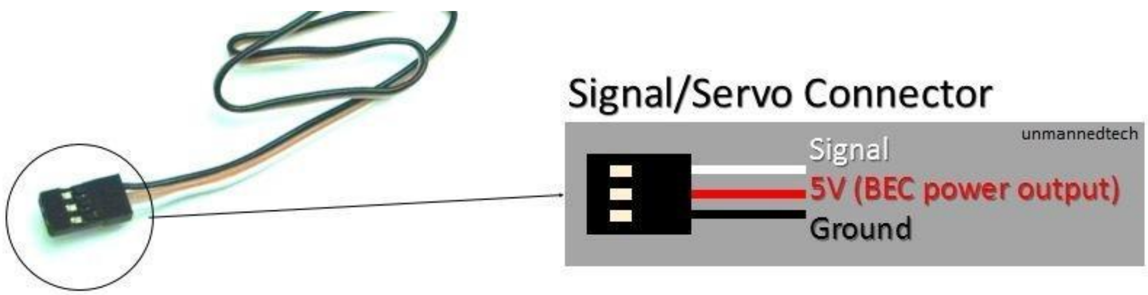


Figure 20: The inputs of ESC

The outputs of ESC

They are 3 cables have the same functionality which it is to pass the current to the motor to turn the engine, to undestand how current passed in this 3 cables we have to study a little what's happens inside the engine(our engine that we need to use).

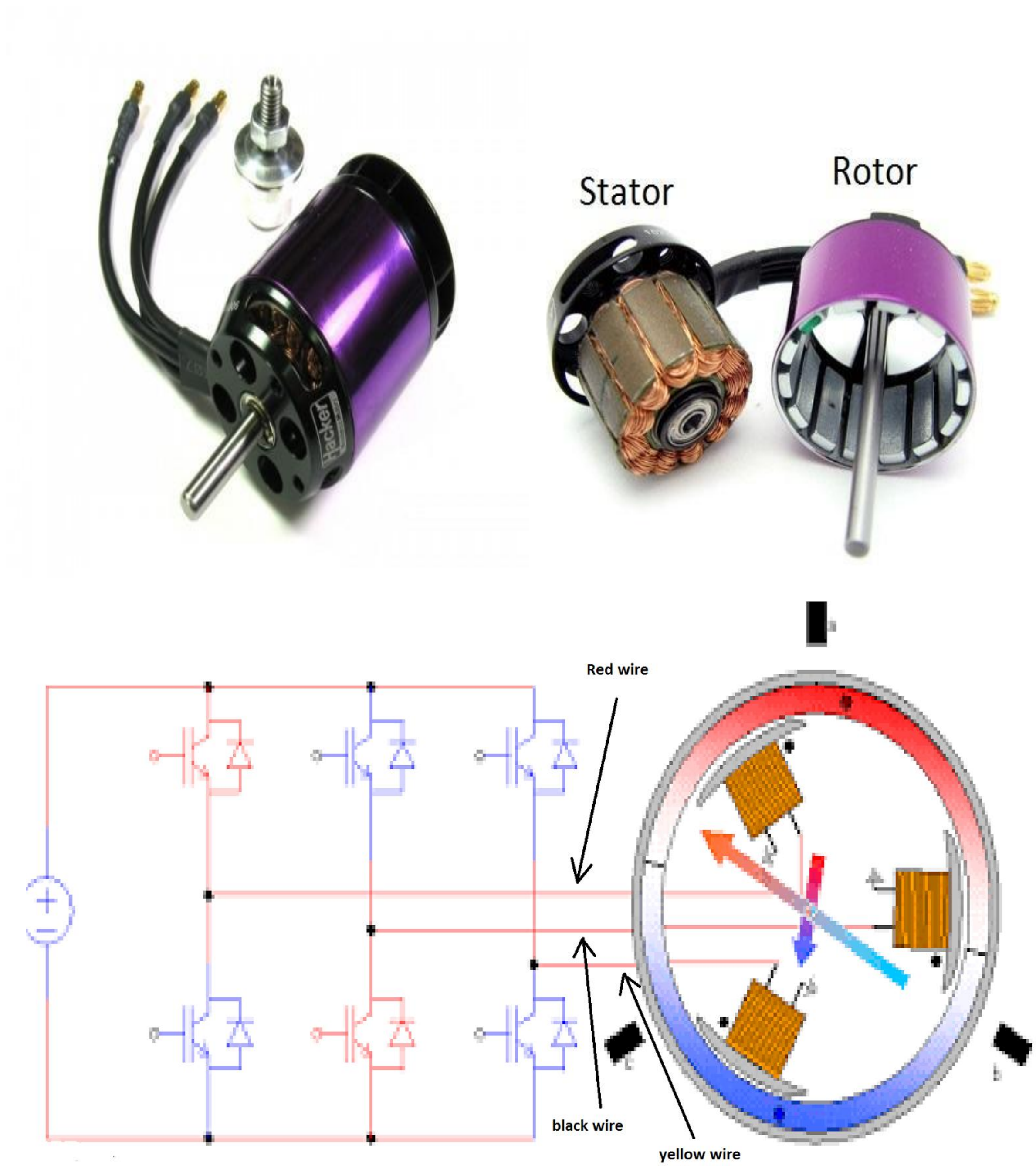


Figure 21: The outputs of ESC

If power is applied to the red wire and the yellow wire, it actually pushes the electricity through the electromagnet to the positive two hours and then becomes powered and pulls the rotor from the rotating foot of motor toward it and then the yellow wire is put in place thereafter and then it restarts the electromagnet at the bottom of the motor so as to pull the rotor until the black wire and the red wire are ignited then which, then pulls the rotor to that position and so on. What’s happen is that the speed controller actually triggers these pairs of wires one after the other faster and faster, also the ESC is listening to the comments it has been sent by the motor.

Note

The Colors of Output wires aren't important.

Power Balance:

In this study we must recognize the power of each component of the drone, in our study we are interested on the battery and the ESC and the motor Brushless and the propeller.

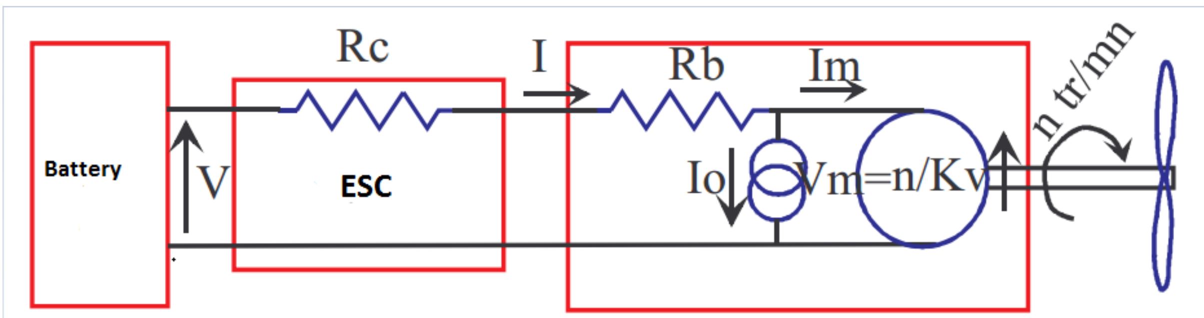


Figure 22: Power Balance

The battery pack gives a current V. The ESC whose MOS switches direct the current, while in the presence of a residual resistance Rc, the resistances of connectors and cable of connection are included in Rc because his value is very small.
The motor whose resistor Rb of the coils also opposes the passage of the current, as well as the opposition voltage endended by the rotation speed, this voltage is represented as a quasi-continuous voltage of value n / Kv, where n is the Speed of rotation in rpm.
Considering the current I0 current consumed by the motor (I0 of most motors is between 1 and 2A) when running without a helix, this current is not zero because it requires a minimum power to overcome friction, Losses of the magnetic circuit.
The power transmitted to the helix is Ph = Vm.Im in Watts.
The motor heating produces the effect of Joule Rb.I.I , so the power balance is:
The power supplied by the battery is Pbatt = V.I
The Power lost by Joule effect is: Pjoule = (Rc + Rb) .I.I
The friction loss and magnetic circuit is: Pfrott = Vm.I0
Now, according to the law of the meshes, V = (Rb + Rc) .I + Vm, therefore Vm = V- (Rb + Rc).I
Therefore Pfrott = [V- (RC + Rb) .I] .I0

The power of the motor transmitted to the helix is Ph = Vm. (I-I0) = [V- (Rb + Rc) .I].(I-I0)

A usual criterion of good operation is a good efficiency, ratio of the useful power transmitted to the propeller on the power supplied by the battery, Rend = Ph / Pbatt.
For the brushless motor one has its Kv is 1000Kv, and its current a vacuum is

I0 = 0,5Amp and its resistance Rb = 0, 090Ohm.
For ESC the value estimated by Rc is Rc = 0, 015Ohm.
For the LIPO the nominal voltage is 6.6Volts.

We need juste to give a values to I to calculate Ph

Note: this study is for one esc,motor and helix,not for four esc,motor and helix.

Chapter III: Dynamics

1. Theory

1.1. Dynamic model

The dynamic model of the quadcopter can be seen as a system where the spatial evolutions of the four-rotor are the outputs and the voltage of each of its motors are the inputs.

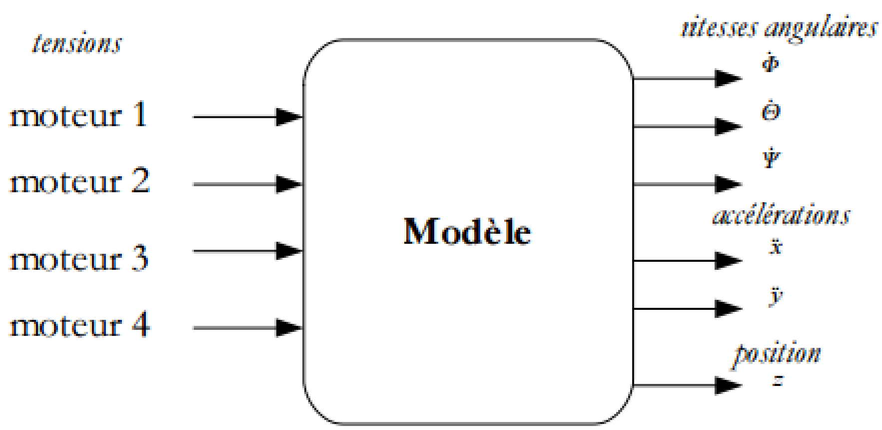


Figure 23: Dynamic model

It is governed by equations which will be developed later in this report.

1.2. Model hypothesis

The quad copter consists of four parallel bars placed in a cross at the ends of which the engines controlling the four rotors with vertical axis are placed.

The weight of the drone is 1 kg for a wingspan of 1 m.

The rotation of the four rotors provides a vertical force, lift, and yaw couple due to drag.

At the center is all the equipment necessary for the proper operation of the drone.

We chose the following axis convention:

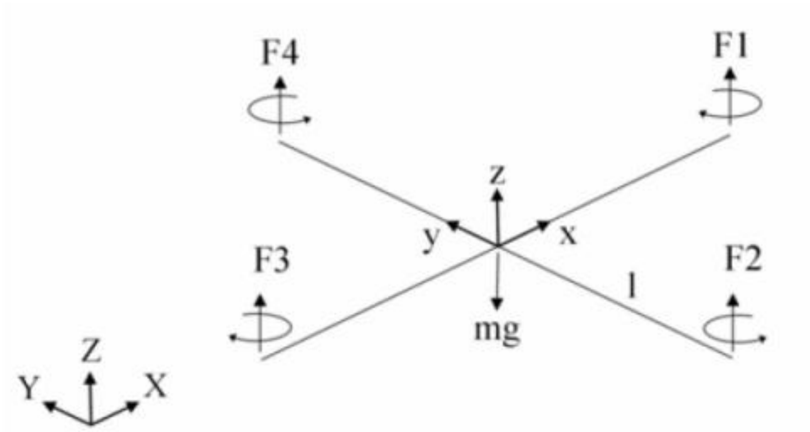


Figure 24: Geometry of the drone

Therefore we must act on the rotation speed of two parallel engines (engine 2 and engine 4) in order to control to control the roll of the drone.

As for pitching, we act on the speeds of engine 1 and engine 3.

The anti-rotation torque generated by the drag must be zero, it is therefore essential that the engines 1 and 3 rotate in the opposite direction to the engines 2 and 4.

Moreover, the axes of the engines are not perfectly vertical: they are slightly inclined towards the center of the drone (approximately 2 °) in order to guarantee a return to the equilibrium position in the event of slight disturbances.

The following assumptions are considered:

- The structure is assumed to be rigid, and symmetric, which implies that the inertia matrix will be assumed to be diagonal.

- The propellers are supposed to be rigid so as to be able to neglect the effect of their deformation during the rotation.

- The center of mass and the origin of the reference point linked to the structure coincide.

- The lift and the drag are proportional to the square of the speed of rotation of the engines, which is an approximation very close to the aerodynamic behavior.

- The rotational speed of the rotors relative to the ground is not taken into account.

- The mass of the quad copter is one kilogram for a wingspan of one meter. - The model is governed by the equations of mechanics which make it evolve on 3 axes.

It undergoes accelerating forces of various types which will be described later.

Figure 25: Different assumptions

1.3. Choice of coordinates and modeling reference

To describe the flight dynamics of the quadcopter figure 1, a set of basic marks and notations have to be defined

The first mark is the inertial frame Ro = {O, Ex, Ey, Ez} or reference mark. This mark is linked to the Earth, and can be considered as Galilean.

Next, we consider Rg = {G, E1g, E2g, E3g} a local coordinate system which origin is the center of gravity of the drone.

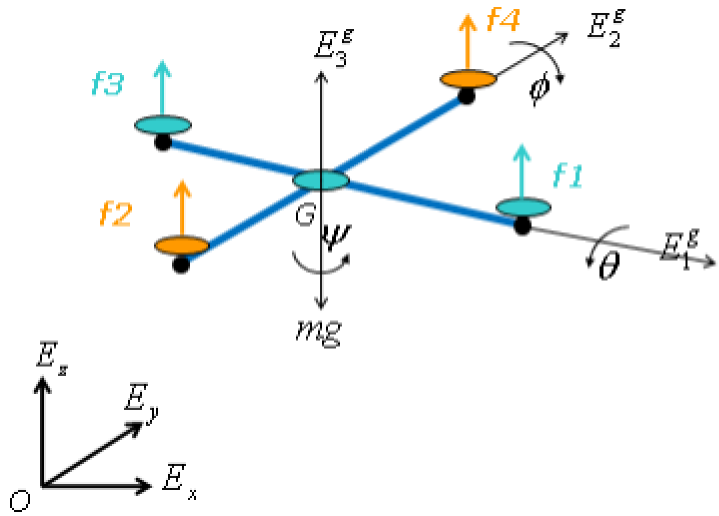


Figure 26: Drone's reference mark

The angles of Euler θ, Ψ, Φ respectively pitch, roll, and yaw are used to determine the orientation of the helicopter mark with respect to the Inertial frame.

1.4. Development of the Lagrange model

The model will be developed according to a Lagrangian approach that is to say according to the kinetic and potential energies. The Lagrange equation is written as followed:

$$\boxed{\Gamma i = \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}i}\right) - \frac{\partial L}{\partial qi}}$$

$$\boxed{L = T - V}$$

Figure 27: Lagrange equation

With :

qi: Generalized coordinates
Γ_i : Generalized Forces Given by Non-Conservative Forces
T: Total kinetic energy
V: Total potential energy

Figure 28: Lagrange equation specifications

The angles of yaw, pitch and roll (aeronautical angles) are defined as follows:

- rotation of around $\vec{x}$ (roll angle with -)
- rotation of around $\vec{y}$ (pitch angle with -22)
- rotation of around $\vec{z}$ (yaw angle with -)

Figure 29: Aeronautical angles

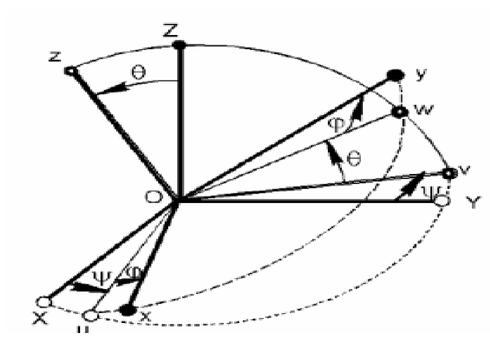


Figure 30: Axis of the aeronautical angles

The writings (t), (t), and (t) will be denoted, and, for simplification.

In order to describe the position and the orientation of the helicopter in the reference R0, yaw, pitch, and roll parameterization is used.

The configuration of the machine is described

The configuration of the apparatus is described by means of three elementary rotations defined by the three angles of rotation.

In order to carry out the transition from the reference R0 to the reference RG, it is necessary to carry out three rotations around the three axes

The matrices relating to these transformations are:

$$R(x,\Phi)=\begin{pmatrix}1 & 0 & 0\\ \cos(\Phi) & -\sin(\Phi) & 0\\ \sin(\Phi) & \cos(\Phi) & 0\end{pmatrix}\qquad R(y,\theta)=\begin{pmatrix}\cos(\theta) & 0 & \sin(\theta)\\ 0 & 1 & 0\\ -\sin(\theta) & 0 & \cos(\theta)\end{pmatrix}\qquad R(z,\psi)=\begin{pmatrix}\cos(\psi) & -\sin(\psi) & 0\\ \sin(\psi) & \cos(\psi) & 0\\ 0 & 0 & 1\end{pmatrix}$$

Figure 31: Transformation matrices

Thus, we multiply these three matrices to obtain the total rotation matrix which is as follows:

$$R(\Phi,\theta,\psi)=\begin{pmatrix}\cos(\psi)\cos(\theta) & \cos(\psi)\sin(\theta)\sin(\Phi)-\sin(\psi)\cos(\Phi) & \cos(\psi)\sin(\theta)\cos(\Phi)+\sin(\psi)\sin(\Phi)\\ \sin(\psi)\cos(\theta) & \sin(\psi)\sin(\theta)\sin(\Phi)+\cos(\psi)\cos(\Phi) & \sin(\psi)\sin(\theta)\cos(\Phi)-\sin(\Phi)\cos(\psi)\\ -\sin(\theta) & \cos(\theta)\sin(\Phi) & \cos(\theta)\cos(\Phi)\end{pmatrix}$$

Figure 32: Multiplication of the transformation matrices

1.5. Speed expression

$\left[\overline{X},\overline{Y},\overline{Z}\right]$ is an Orthonormal base constituting a fixed reference frame.

If the solid undergoes three successive rotations according to the aeronautical angles, then

$$r_{X,Y,Z}(x,y,z)=R(\Phi,\theta,\psi)\begin{pmatrix}x\\ y\\ z\end{pmatrix}$$

Using the equation obtained previously, and deriving from it, we obtain the velocities:

$$v_X(x,y,z) = \begin{pmatrix} v_{x_x} & v_{x_y} & v_{x_z} \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

$$v_Y(x,y,z) = \begin{pmatrix} v_{y_x} & v_{y_y} & v_{y_z} \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

$$v_Z(x,y,z) = \begin{pmatrix} v_{z_x} & v_{z_y} & v_{z_z} \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

Figure 33: Velocities

Thus the square of the standard of the velocity is:

$$v^2(x,y,z) = v_x^2 + v_y^2 + v_z^2$$

$$v^2(x,y,z) = \begin{pmatrix} v_{x_x} & v_{x_y} & v_{x_z} \end{pmatrix} A \begin{pmatrix} v_{x_x} \\ v_{x_y} \\ v_{x_z} \end{pmatrix} + \begin{pmatrix} v_{y_x} & v_{y_y} & v_{y_z} \end{pmatrix} A \begin{pmatrix} v_{y_x} \\ v_{y_y} \\ v_{y_z} \end{pmatrix} + \begin{pmatrix} v_{z_x} & v_{z_y} & v_{z_z} \end{pmatrix} A \begin{pmatrix} v_{z_x} \\ v_{z_y} \\ v_{z_z} \end{pmatrix}$$

$$\text{avec } A = \begin{pmatrix} x^2 & xy & xz \\ xy & y^2 & yz \\ xz & yz & z^2 \end{pmatrix}$$

$$\begin{aligned} v^2(x,y,z) = {} & (v_{x_x}^2 + v_{y_x}^2 + v_{z_x}^2)x^2 + (v_{x_y}^2 + v_{y_y}^2 + v_{z_y}^2)y^2 + (v_{x_z}^2 + v_{y_z}^2 + v_{z_z}^2)z^2 \\ & + 2xy(v_{x_x}v_{x_y} + v_{y_x}v_{y_y} + v_{z_x}v_{z_y}) + 2xz(v_{x_x}v_{x_z} + v_{y_x}v_{y_z} + v_{z_x}v_{z_z}) + 2yz(v_{x_y}v_{x_z} + v_{y_y}v_{y_z} + v_{z_y}v_{z_z}) \end{aligned}$$

Figure 34: Square of the standard of the velocity

The final expression of the square of the standard of velocity is written as follows:

$$v^2(x,y,z) = (y^2+z^2)\left[\dot{\psi}^2\sin^2(\theta) - 2\dot{\Phi}\dot{\psi}\sin(\theta) + \dot{\Phi}^2\right]$$
$$+(x^2+z^2)\left[\dot{\psi}^2\sin^2(\Phi)\cos^2(\theta) + 2\sin(\Phi)\cos(\Phi)\cos(\theta)\dot{\theta}\dot{\psi} + \cos^2(\Phi)\dot{\theta}^2\right]$$
$$+(x^2+y^2)\left[\dot{\psi}^2\cos^2(\Phi)\cos^2(\theta) - 2\sin(\Phi)\cos(\Phi)\cos(\theta)\dot{\theta}\dot{\psi} + \sin^2(\Phi)\dot{\theta}^2\right]$$
$$+2xy\left[\dot{\psi}^2\sin(\Phi)\sin(\theta)\cos(\theta) + \dot{\psi}(\cos(\Phi)\sin(\theta)\dot{\theta} - \sin(\Phi)\cos(\theta)\dot{\Phi}) - \cos(\Phi)\dot{\Phi}\dot{\theta}\right]$$
$$+2xz\left[\dot{\psi}^2\cos(\Phi)\sin(\theta)\cos(\theta) + \dot{\psi}(-\cos(\Phi)\cos(\theta)\dot{\Phi} - \sin(\Phi)\sin(\theta)\dot{\theta}) + \sin(\Phi)\dot{\Phi}\dot{\theta}\right]$$
$$+2yz\left[-\dot{\psi}^2\sin(\Phi)\cos(\Phi)\cos^2(\theta) + \dot{\psi}(\sin^2(\Phi)\cos(\theta)\dot{\theta} - \cos^2(\Phi)\cos(\theta)\dot{\theta}) + \sin(\Phi)\cos(\Phi)\dot{\theta}^2\right]$$

Figure 35: Final expression of the square of the standard of velocity

1.6. Expression of the Kinetic Energy

Kinetic energy is written as a function of the mass and the square of the velocity as follows:

$$T = \frac{1}{2}mv^2$$

Figure 36: Expression of the Kinetic Energy

After development of the calculations, we show the moments of inertia and products of inertia (zero given that the inertia matrix is diagonal).

The final expression of the kinetic energy obtained is thus written as follows:

$$\boxed{T = \frac{1}{2}I_x(\dot{\Phi} - \dot{\psi}\sin(\theta))^2 + \frac{1}{2}I_y(\dot{\theta}\cos(\Phi) + \dot{\psi}\sin(\Phi)\cos(\theta))^2 + \frac{1}{2}I_z(\dot{\theta}\sin(\Phi) - \dot{\psi}\cos(\Phi)\cos(\theta))^2}$$

$$\text{avec } I_x = \frac{1}{2}\int(y^2+z^2)dm,\ I_y = \frac{1}{2}\int(x^2+z^2)dm,\ I_z = \frac{1}{2}\int(x^2+y^2)dm$$

Figure 37: Final expression of the kinetic energy

1.7. Expression of the Potential Energy

The potential energy is as follows:

$$V = g\int(-\sin(\theta)x + \sin(\Phi)\cos(\theta)y + \cos(\Phi)\cos(\theta)z)dm$$

Figure 38: Expression of the Potential Energy

The final result of the expression of the potential energy is written:

$$\boxed{V = \int xdm(-g\sin(\theta)) + \int ydm(g\sin(\Phi)\cos(\theta)) + \int zdm(g\cos(\Phi)\cos(\theta))}$$

Figure 39: Final expression of the Potential Energy

1.8. Equations of motion

Roll equation:

$$\Gamma_{\Phi} = \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\Phi}}\right) - \frac{\partial L}{\partial \Phi} = \tau_x$$

Pitch equation:

$$\Gamma_{\theta} = \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}}\right) - \frac{\partial L}{\partial \theta} = \tau_y$$

Yaw equation:

$$\Gamma_{\psi} = \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\psi}}\right) - \frac{\partial L}{\partial \psi} = \tau_z$$

Figure 40: Equations of motion

After developing the calculations, we obtain the following expressions:

$$
\begin{aligned}
\Gamma_{\Phi} = {} & \ddot{\Phi} I_x \\
& - \ddot{\psi} \sin(\theta) I_x \\
& - \dot{\theta}\dot{\psi} \cos(\theta)\left[\cos(2\Phi)(I_y - I_z) + I_x\right] \\
& - \dot{\psi}^2 \cos^2(\theta) \frac{\sin(2\Phi)}{2}(I_y - I_z) \\
& - \dot{\theta}^2 \frac{\sin(2\Phi)}{2}(I_z - I_y) \\
& + g\cos(\theta)\cos(\Phi)\int y\,dm \\
& - g\cos(\theta)\sin(\Phi)\int z\,dm
\end{aligned}
$$

$$
\begin{aligned}
\Gamma_{\Phi} = {} & \dot{\omega}_x I_x + \left(I_z - I_y\right)\omega_y \omega_z \\
& + g\cos(\theta)\cos(\Phi)\int y\,dm \\
& - g\cos(\theta)\sin(\Phi)\int z\,dm
\end{aligned}
$$

Figure 41: Roll Equation

$$\begin{aligned}\Gamma_{\theta} = {} & \ddot{\theta}\left[\cos^{2}(\Phi)I_{y} + \sin^{2}(\Phi)I_{z}\right] \\ & + \ddot{\psi}\cos(\theta)\frac{\sin(2\Phi)}{2}\left[I_{y} - I_{z}\right] \\ & + \dot{\theta}\dot{\Phi}\sin(2\Phi)\left[I_{z} - I_{y}\right] \\ & + \dot{\psi}\dot{\Phi}\cos(\theta)\left[\cos(2\Phi)\left(I_{y} - I_{z}\right) + I_{x}\right] \\ & - \dot{\psi}^{2}\frac{\sin(2\theta)}{2}\left[I_{x} - \cos^{2}(\Phi)I_{z} - \sin^{2}(\Phi)I_{y}\right] \\ & - \int xdm(g\cos(\theta)) \\ & - \int ydm(g\sin(\Phi)\sin(\theta)) \\ & - \int zdm(g\cos(\Phi)\sin(\theta))\end{aligned}$$

$$\begin{aligned}\Gamma_{\theta} = {} & -\sin(\Phi)\left[I_{z}\dot{\omega}_{z} + (I_{y} - I_{x})\omega_{x}\omega_{y}\right] \\ & + \cos(\Phi)\left[I_{y}\dot{\omega}_{y} + (I_{x} - I_{z})\omega_{x}\omega_{z}\right] \\ & - \int xdm(g\cos(\theta)) \\ & - \int ydm(g\sin(\Phi)\sin(\theta)) \\ & - \int zdm(g\cos(\Phi)\sin(\theta))\end{aligned}$$

Figure 42: Pitch Equation

$$
\begin{aligned}
\Gamma_{\psi} = {} & \ddot{\psi}\left[I_x \sin^2(\theta) + \cos^2(\theta)(\sin^2(\Phi) I_y + \cos^2(\Phi) I_z)\right] \\
& - \ddot{\Phi} \sin(\theta) I_x + \ddot{\theta} \frac{\sin(2\Phi)}{2} \cos(\theta)\left[I_y - I_z\right] \\
& + \dot{\psi}\dot{\theta} \sin(2\theta)\left[I_x - \sin^2(\Phi) I_y - \cos^2(\Phi) I_z\right] \\
& - \dot{\Phi}\dot{\theta} \cos(\theta)\left[I_x + \cos(2\Phi)(I_z - I_y)\right] \\
& + \dot{\psi}\dot{\Phi} \sin(2\Phi) \cos^2(\theta)\left[I_y - I_z\right] \\
& + \dot{\theta}^2 \frac{\sin(2\Phi)}{2} \sin(\theta)\left[I_z - I_y\right]
\end{aligned}
$$

$$
\begin{aligned}
\Gamma_{\psi} = {} & -\sin(\theta)\left[I_x \dot{\omega}_x + (I_z - I_y)\omega_y \omega_z\right] \\
& + \cos(\Phi)\cos(\theta)\left[I_z \dot{\omega}_z + (I_y - I_x)\omega_x \omega_y\right] \\
& + \sin(\Phi)\cos(\theta)\left[I_y \dot{\omega}_y + (I_x - I_z)\omega_x \omega_z\right]
\end{aligned}
$$

Figure 43: Yaw Equation

1.9. Expression of non-conservative forces

The lift

Lift is the force that allows the drone to climb and maintain its altitude.

It is generated by the four rotating rotors.

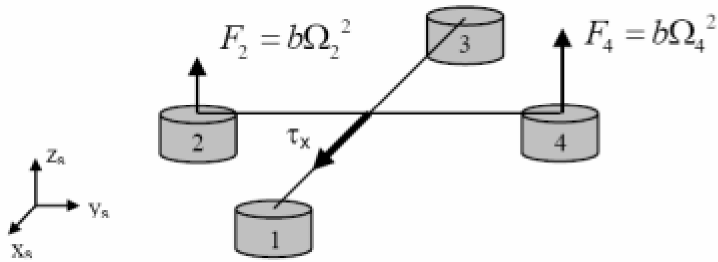


Figure 44: Moment due to engine thrust

The lift of the engines creates torques in the direction of the X and Y axis:

On the roll axis:

$$\boxed{\tau_x = bl(\Omega_4^2 - \Omega_2^2)}$$

Figure 45: Torques on the roll axis

On the pitch axis:

$$\boxed{\tau_y = bl(\Omega_3^2 - \Omega_1^2)}$$

Figure 46: Torques on the pitch axis

With:

i^2: The speed of each engine squared in (rad / s) ²

b: The range coefficient in(Kg.m/rad²)

l: The half-span of the quadrirotor in meters.

1.10.Calculation of the thrust coefficient

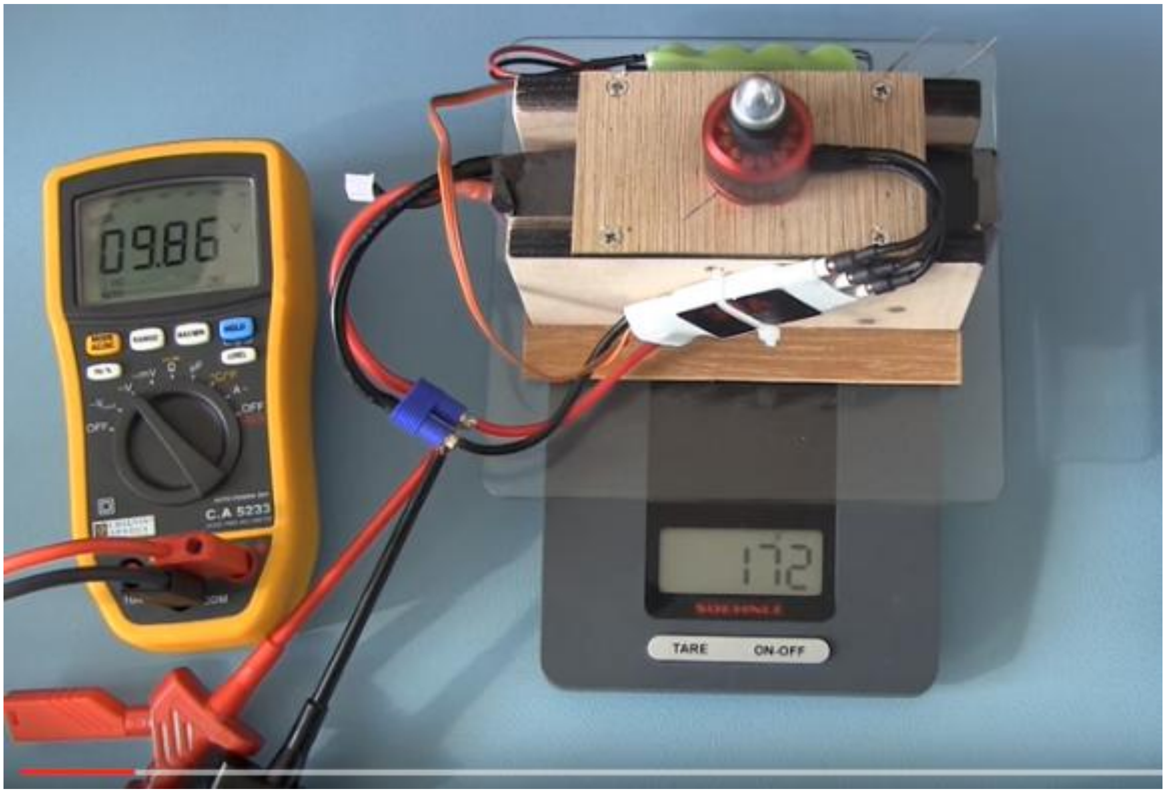


Figure 47: Calculation of the thrust coefficient

The force generated by the set {motor + helix} is of the form: $\boxed{F_i = b\Omega^2}$

With:

The speed of rotation of the propeller (rad / s)

At full power, the engines have a rotational speed of 11000 rpm, and can lift 500 grams each. Therefore:

Fi = 5 N

Ωi= 1151 rad/s

We thus obtain: b= 3,77x 10 -6kg.m.rad-²

The drag:

It is the result of the friction of the air on the quadrirotor, it is parallel and opposite to the trajectory.

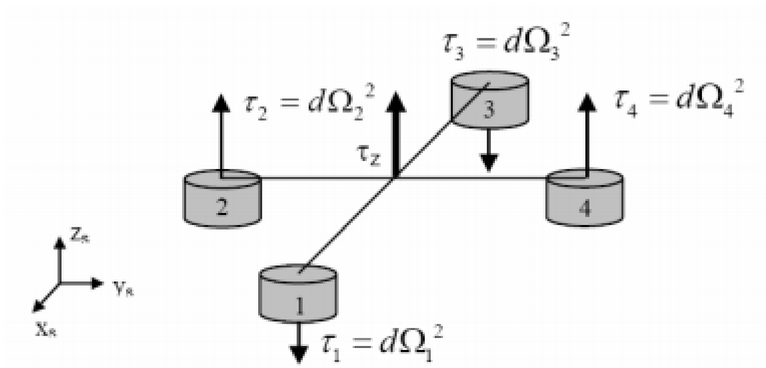


Figure 48: Moment due to drag of propellers

The drag of the propellers creates a vertical torque:

$$\boxed{\tau_z = d(\Omega_1^2 + \Omega_3^2 - \Omega_2^2 - \Omega_4^2)}$$

Figure 49: Vertical Torque

With:

d: The drag coefficient in kg.m² / rad² (constant between the drag and the speed of an engine).

1.11.Calculus of the drag coefficient d

We perform the following experiment:

- We place the drone on a support which allows a free rotation according to the vertical axis (the lace).
- We enter a known power setpoint in two of the four engines (1 and 3 for example)

- We are timing the time taken by the drone to perform a quarter turn (=/2).

The relationship between the yaw angle and engine speeds is as follows:

$$\ddot{\psi}=\frac{d(\Omega_1^2+\Omega_3^2-\Omega_2^2-\Omega_4^2)}{Iz}$$

Figure 50: Relationship between the yaw angle and engine speeds

According to the drone study, the only possible movement is that of the yaw.

So:

$$\frac{(Ix-Iy)}{Iz}\dot{\theta}\dot{\Phi}=0$$

The law of yaw angle, obtained after integration twice [considering initial zero conditions], is in the form:

$$\boxed{\psi=\frac{d(\Omega_1^2+\Omega_3^2-\Omega_2^2-\Omega_4^2)}{Iz}\frac{t^2}{2}}$$

Figure 51: Law of yaw angle

- We put the engines 1 and 3 at half power. [5400 rpm, in our case?]
- We put the engines 2 and 4 off.
- We perform a quarter turn:

We then obtain:

$$\frac{\pi}{2}=\frac{d2\Omega^2}{Iz}\frac{t^2}{2}$$

$$\Rightarrow d=\frac{\pi Iz}{2\Omega^2 t^2}$$

Figure 52: Performance of a quarter turn

1.12.The gyroscopic effect

When the quadrotor rotates on two axes, this force appears on the third axis and tends to resist the movements of the quadrirotor.

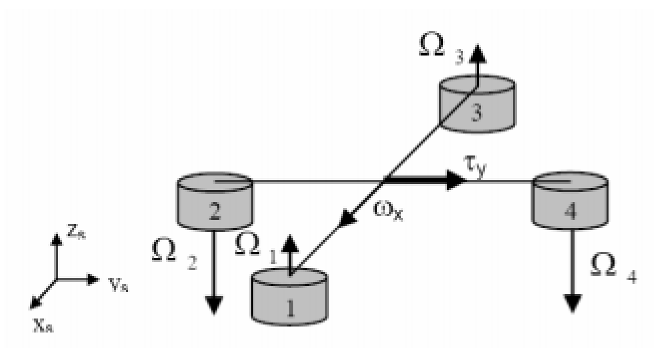


Figure 53: Gyroscopic effect

Therefore:

$$\tau_x = I_{rotor}\omega_y(\Omega_3+\Omega_1-\Omega_2-\Omega_4) \qquad \tau_y = I_{rotor}\omega_x(-\Omega_3-\Omega_1+\Omega_2+\Omega_4)$$

With:

I_{rotor} The moment of inertia of the engine in kg.m²

ω_x The angular velocity along the x-axis in rad / s

By summing all the pairs, we then obtain:

$$\begin{aligned}
\tau_x &= bl(\Omega_4^2 - \Omega_2^2) + I_{rotor}\omega_y(\Omega_3 + \Omega_1 - \Omega_2 - \Omega_4) \\
\tau_y &= bl(\Omega_3^2 - \Omega_1^2) + I_{rotor}\omega_x(-\Omega_3 - \Omega_1 + \Omega_2 + \Omega_4) \\
\tau_z &= d(\Omega_1^2 + \Omega_3^2 - \Omega_2^2 - \Omega_4^2)
\end{aligned}$$

Figure 54: Gyroscopic effect equations

1.13.Equations of angular velocity

By projecting the three preceding forces and adding the effect on the acceleration of the moments of inertia on each axis, the quadrirotor then reacts in roll, pitch and yaw in the following manner:

$$\ddot{\psi} = \frac{d(\Omega_1^2 + \Omega_3^2 - \Omega_2^2 - \Omega_4^2)}{Iz} + \frac{(Ix - Iy)}{Iz}\dot{\theta}\dot{\Phi}$$

$$\ddot{\theta} = \frac{-I_{rotor}\,\dot{\phi}(\Omega_1 + \Omega_3 - \Omega_2 - \Omega_4)}{I_y} + \frac{(Iz - Ix)}{I_y}\dot{\phi}\dot{\psi} + \frac{bl(\Omega_3^2 - \Omega_1^2)}{I_y}$$

$$\ddot{\phi} = \frac{I_{rotor}\,\dot{\theta}(\Omega_1 + \Omega_3 - \Omega_2 - \Omega_4)}{I_x} + \frac{(Iy - Iz)}{I_x}\dot{\theta}\dot{\psi} + \frac{bl(\Omega_4^2 - \Omega_2^2)}{I_x}$$

Figure 55: Equations of angular velocity

Also, the four-rotor undergoes accelerations on the three axes of space.

These accelerations depend on the lift generated by the motors denoted Ti which is equal to:

$$T_i = b.\Omega_i^2 \quad i \in \{1, 2, 3, 4\}$$

1.14.Motor Dynamic

The transfer function of an electric engine is of the second order and is written in the following form:

$$\boxed{H(p)=\frac{K}{K^2+Rf+(Rj+Lf)p+LJp^2)}}$$

K : gain du moteur en V.s/rad
R : résistance interne du moteur en Ω
L : inductance en H
f : frottements
J : inertie du rotor en g.cm²

Figure 56: Second degree Transfer function

Thus, this transfer function can be close to a first order by neglecting certain elements.

Indeed, the inductance is of the order of milliHenry, it is therefore negligible in front of the resistance of the engine which is of the order of ten tens of Ohm.

Similarly, the friction of an engine is negligible in front of the inertia of the rotor.

We thus obtain:

$$H(p)=\frac{K}{K^2+RJp} \quad \Rightarrow \quad \boxed{H(p)=\frac{k}{1+\tau p}}$$

Figure 57: First degree Transfer function

k : Motor gain in rad / s.volt
τ : Engine time constant in seconds

The engine gain is given by the manufacturer.

The time constant is determined by performing a sound recording of the engine response at a voltage step.

2. Implementation

2.1. Modelisation with Matlab Simulinkfor stabilisation (with PID)

2.1.1. What is Simulink

Simulink® is a block diagram environment for multidomain simulation and Model-Based Design. It supports simulation, automatic code generation, and continuous test and verification of embedded systems.

Simulink provides a graphical editor, customizable block libraries, and solvers for modeling and simulating dynamic systems. It is integrated with MATLAB®, enabling you to incorporate MATLAB algorithms into models and export simulation results to MATLAB for further analysis.

[https://www.mathworks.com/products/simulink.html]

2.1.2. What is PID

PID (proportional, integral, differential) is a control algorithm that aims at compensating for deviations of the system from a pre-determined response. A PID controller is a type of error correcting process control system.

There are three primary components to think about in a PID control loop:

- Each component is prefixed with a gain constant, and when added together, give the instantaneous control value that is used to drive the system. Typically, we are generating a voltage to control the system, so each component can be thought of as contributing a particular voltage to the final output.

- There will be voltage corresponding to the current state of the system (position, temperature, etc.) that is called "Process Variable" or PV. The PV is the value passed to the PID control loop to tell it about the state of the system. There will also be a "Set Point" (SP) voltage, corresponding to the state we wish the PV to reach. Basically, we want the PID loop to drive the system so that SP and PV are equal.

- Third, there will be a control voltage, which corresponds to the instantaneous voltage value used to drive the system towards its set point SP voltage. The control voltage can be thought of as what is actually sent to the system to steer it where we want it to go. It's analogous to a gas pedal that the control loop is controlling.

The PID algorithm is shown in Equation (1.1).

$$u(t) = MV(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d}{dt} e(t)$$

Figure 58: PID Algorithm

There are proportional, integral and differential parts in Equation.

The constants Kp, Ki, and Kd are used to set the sign and contribution gain of each part of this equation.

e(t) is the proportional "error" corresponding to SP - PV.

The variable t corresponds to the current time in our system, and is simply a variable of integration.

The proportional portion of the equation takes into account how far away our PV is from our SP. The differential part takes into account how fast we are moving (if we move to fast near our SP , we will over shoot), and can be used to reduce the proportional portion if we are moving too fast, or speed us up if we are experiencing resistance despite our proportional contribution.

The integral part of the equation takes into account how long we have been off of the set point, contributing more to our output the longer we are missing the SP .

This is important because our P and D contributions will typically lead our PV to sag slightly above or below our SP variable. (PID controller, 2013)

PID controllers offer a simple but effective solution to stabilize the aircraft because they make it possible to treat every variable independently within a limited range in which the behaviour of the quadcopter is approximately linear (Bouabdallah et al., 2005; Castillo et al., 2005).

2.2. Application of stabilization using PID

As mentioned above, the drone is controlled by four commands:

* Power (which allows to control the altitude)

* A roll

* A pitch

* A yaw.

These commands are then sent to the various engines.

The power command is sent to all engines, just like the yaw.

Pitch and roll are obtained by controlling only two engines (1 and 3 for pitching and 2 and 4 for roll).

The quadrirotor subsystem includes the mechanical equations that model the dynamics of the system.

The implemented correctors are Proportional Integral Derivatives (PID) and then we use the LQ command. However, it is always possible to study the type of correctors to be implemented in order to obtain a satisfactory dynamic.

The PID corrector:

The PID is a corrector used in automatics to stabilize mechanical systems. In order to apply a PID, it is required to observe the difference between the value around which it is desired to stabilize, the setpoint, and the actual value observed on the system. This difference is called an error.

• A proportional action (P): we apply a gain Kp to the error.

• An integral action (I): we integrate the error, and we multiply the result by a gain Ki.

• A derived action (D): we derive the error, and we multiply the result by a gain Kd.

In our case, we chose to use a PID corrector on pitch, roll and yaw angles.

2.3. Simulink modeling of the system

The previous equations have been translated under Simulink by the previous teams in order to determine a control algorithm to be embarked on the quadro-rotor.

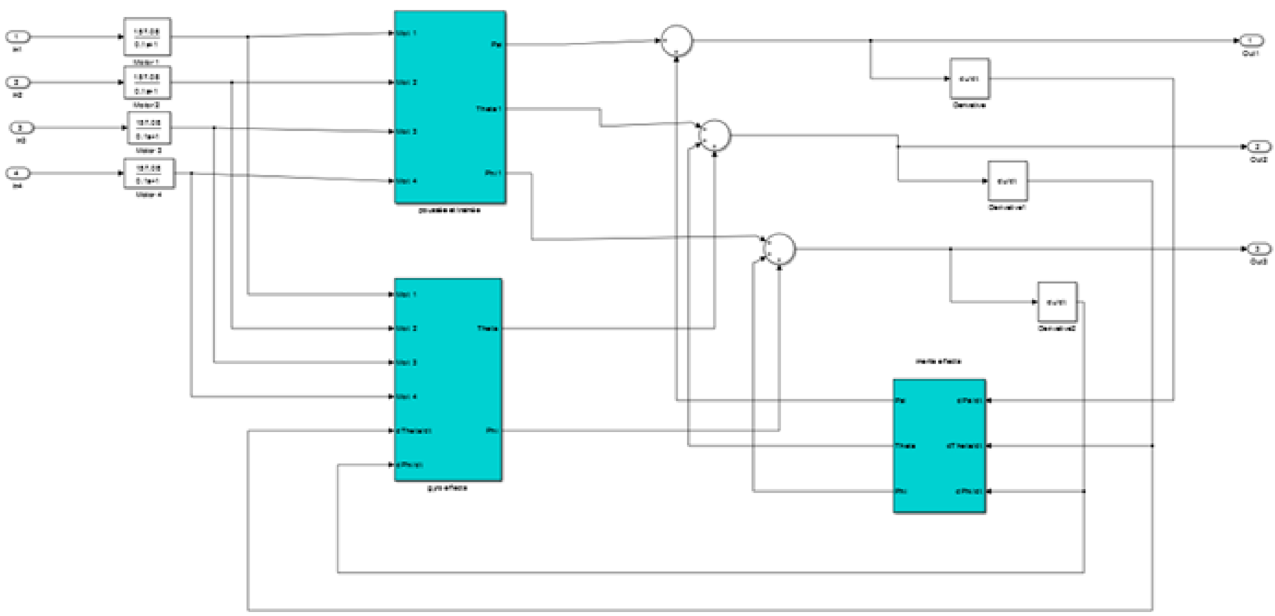


Figure 59: Simulink modeling of the system

After the modeling of the forces, we can confirm that the system is totally unstable.

So, we have to control it through a PID corrector.

The corrector receives the difference between the angle of the quadro-rotor given by integration of the gyroscopes and the angle setpoint and the deviation between its given position by a double integration of the accelerometers and the setpoint in position.

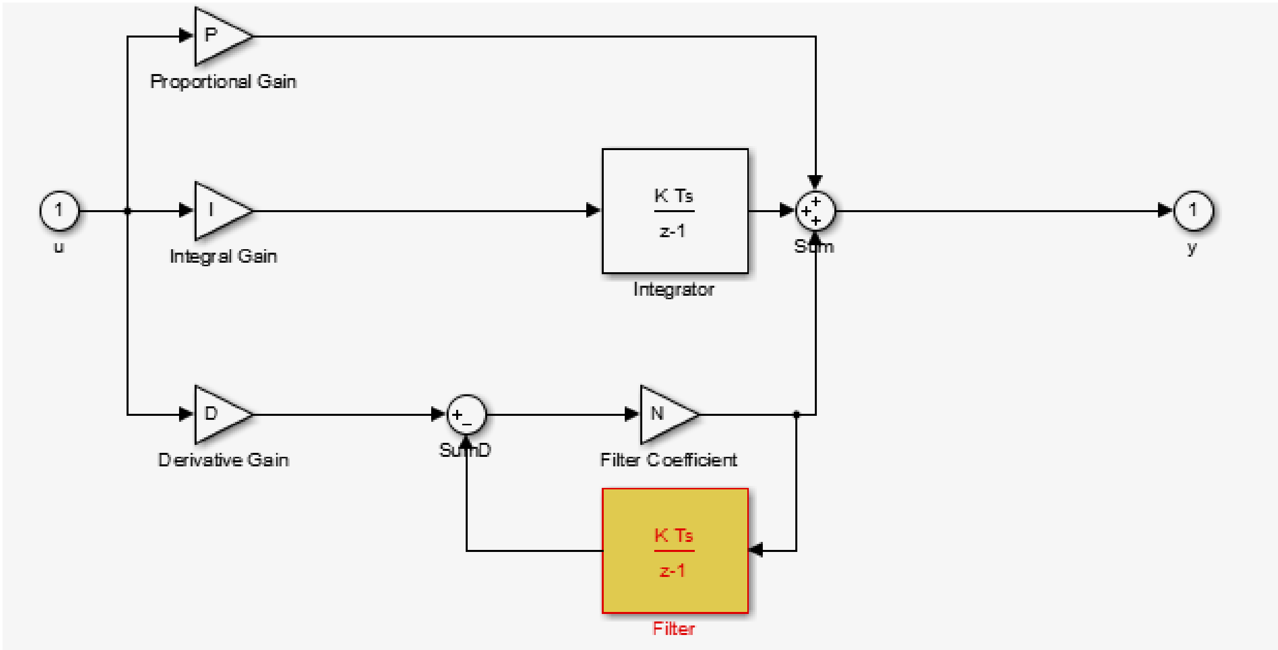


Figure 60: PID Model used

2.4. Modeling of thrust and drag

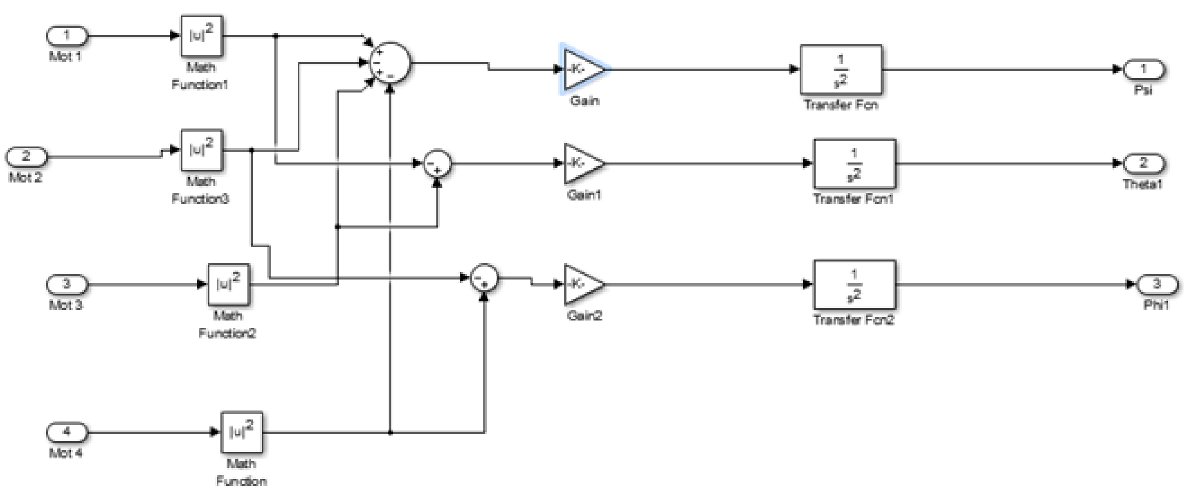


Figure 61: Modeling under Simulink

The figures show the modeling of the effect of inertia, and the gyroscopic effect, under Simulink.

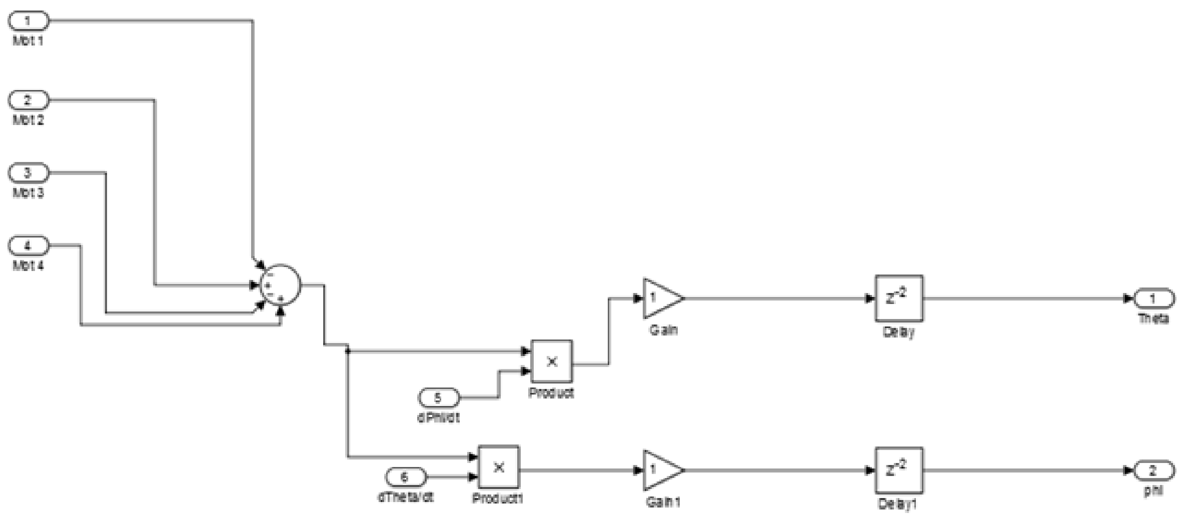


Figure 62: Modeling the gyroscopic effect

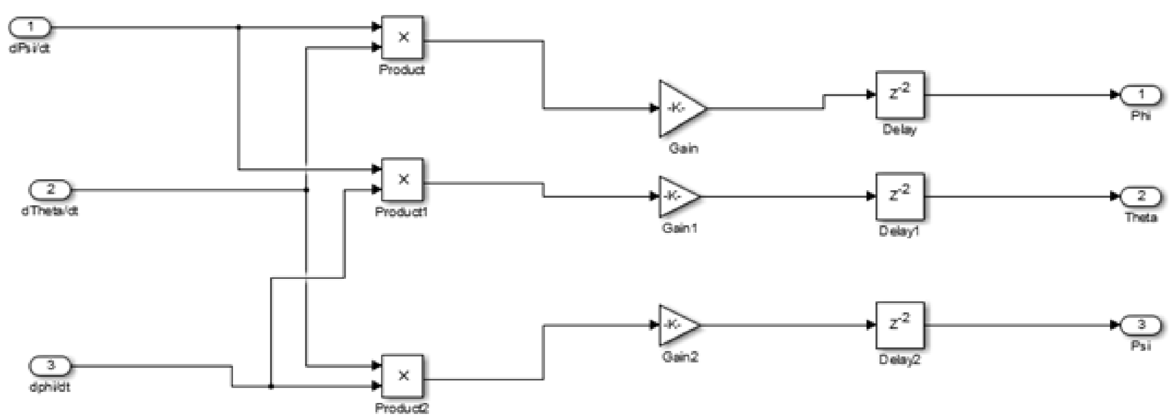


Figure 63: Modeling the effect of inertia

The angular control therefore seeks to stabilize the quadrotor by considering the instructions for yaw, pitch and roll.

PID controllers are used for angles around the three axes.

The power setpoint is the basis for the addition of each value in order to calculate the voltages.

The lace is added to the engines, which turn in the lace direction and subtract from the others.

The pitch is added to an engine and subtracted from the one in front and turns in the same direction. Roll performs the tension of the other pair of motors in the same way.

It is necessary to increase and reduce at the same time the voltages of the motors which rotate in the same direction, so that the quadrirotor is stable in yaw.

After all the saturation limits the voltage between 0 and 5 V:

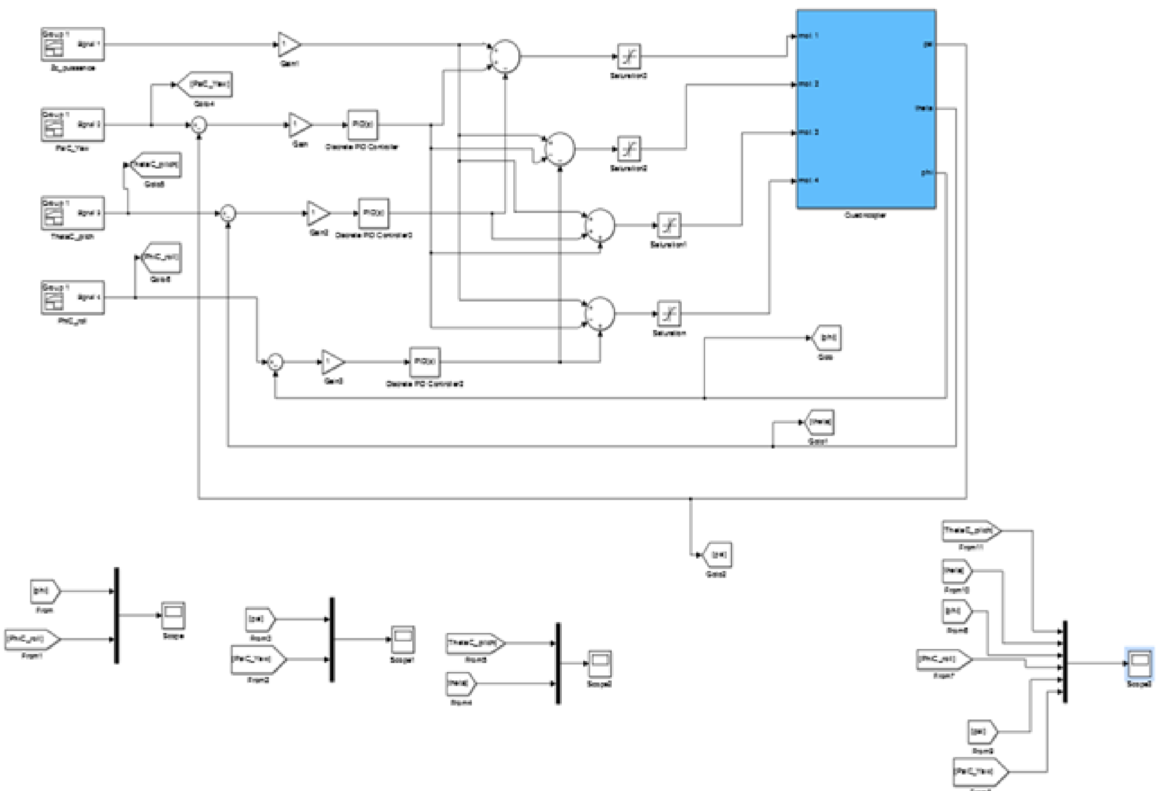


Figure 64: Global control diagram

For the actual model the controller consists of three parts:

- Acquisition of sensor values,
- Calculation of values for the PWM duty cycle
- Output for generating PWM signals for motors.

In our Simulink model the voltage of the motors is directly output and the speed of the propellers is calculated from the voltages.

2.5. Results

2.5.1. Non-simultaneous steps

The system is subject to three non-simultaneous steps. For Proportional-Derivative type correctors (P + Td * s), the following curves are obtained:

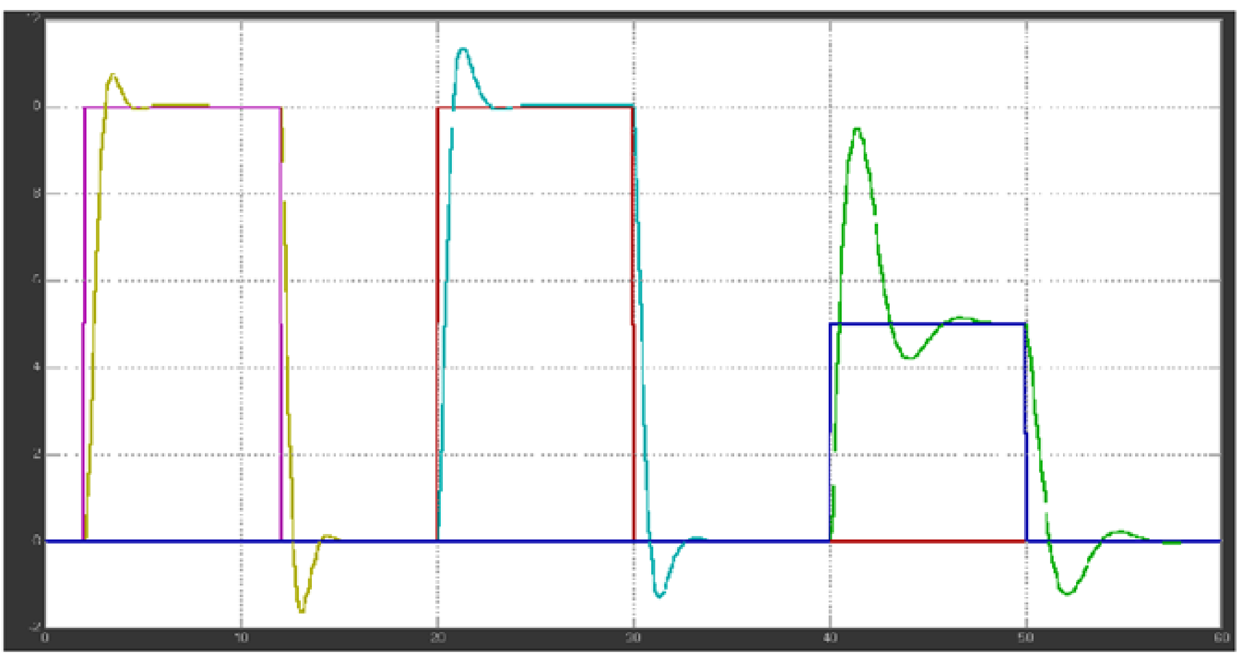


Figure 65: Non-simultaneous steps

Since the setpoints are not simultaneous, the effects of inertia and the gyroscopic effects are virtually zero.

2.5.2. Simultaneous steps

In order to study the influence of other effects due to the motors, it is necessary to order three steps simultaneously.

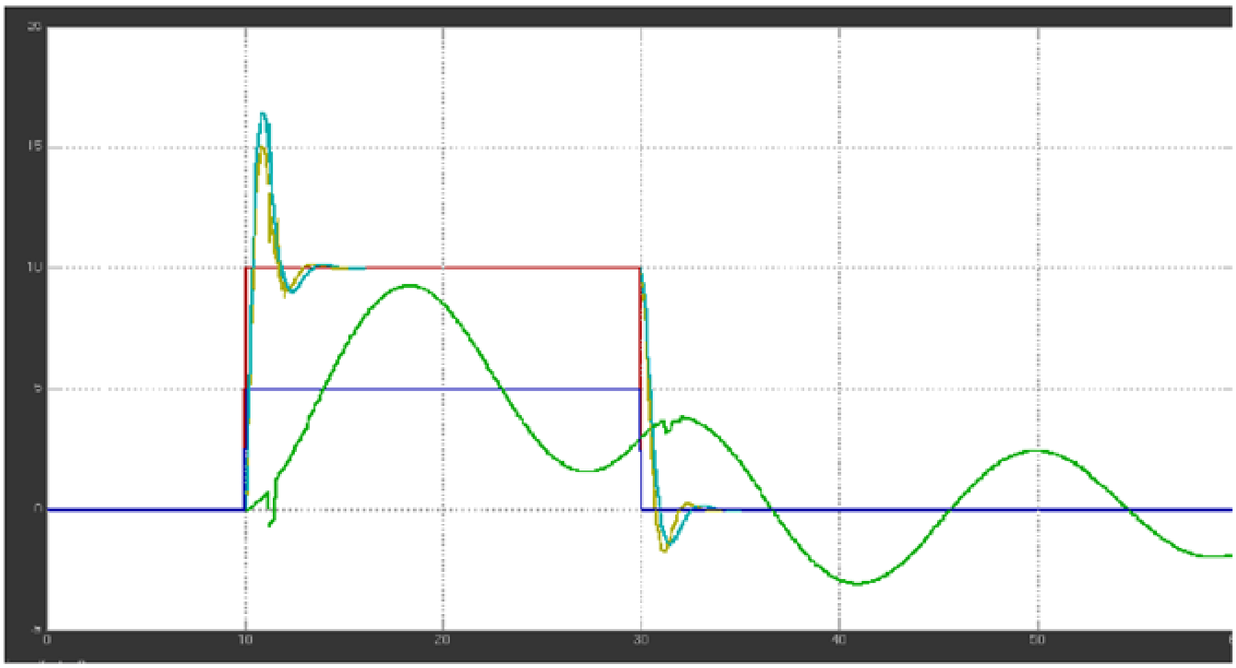


Figure 66: Simultaneous steps

We are interested in the movement of the yaw:

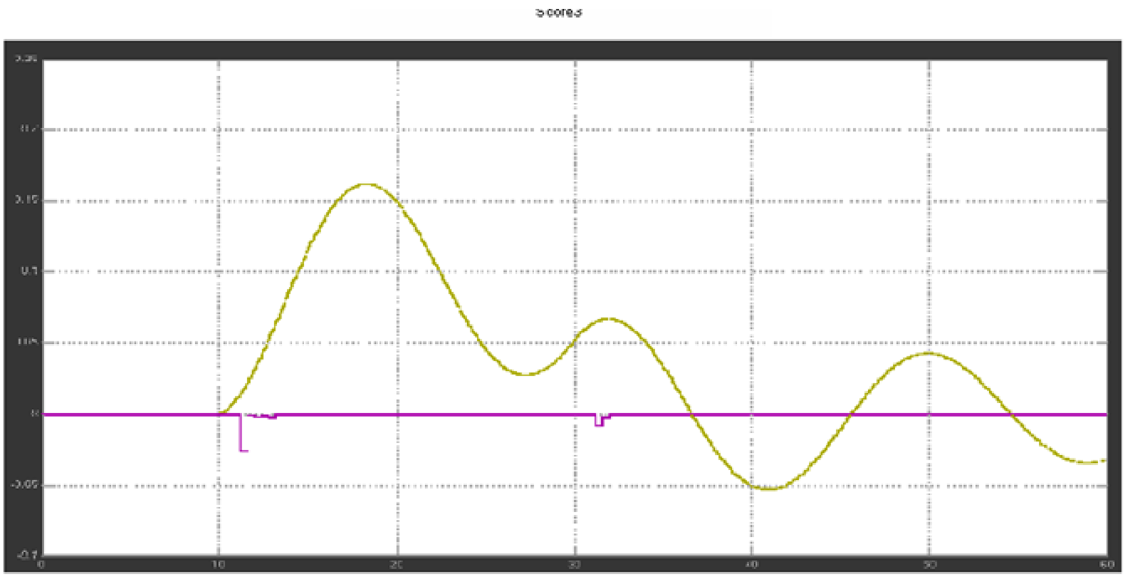


Figure 67: Movement of the yaw

2.5.3. Conclusion

It is noted that the inertia effects and the gyroscopic effects are negligible with respect to the thrust and the drag of the motors along the three axes. This has the effect of decoupling the problem: if a roll or pitch setpoint implies yaw movement, a yaw setpoint will have practically no effect on the other two axes of rotation.

In the following, we will only focus on the thrust and drag of the motors.

From what has been seen in the previous section, the PID correctors can be set independently (except for the lace). First, the correctors stabilizing the roll and pitch and then the yaw will be adjusted in the case of three simultaneous rungs. Indeed, it is in the case of simultaneous rungs that the yaw induced by the roll and the pitch will be the most important.

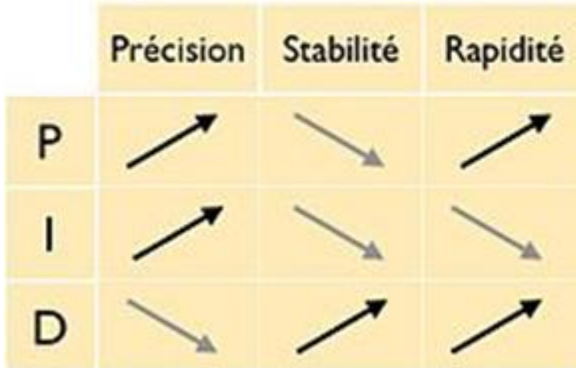


Figure 68: PID Correctors

If one tries to put in place a simple proportional corrector as in the case of the figure 6.9 for the roll, one realizes that one has an instability for a setpoint in step. It is not possible to stabilize the system with simple proportional correctors. Indeed, the system corrects itself too late. To correct this correction delay problem, it is necessary to introduce a derivative term into the corrector which will increase the reaction rate of the system.

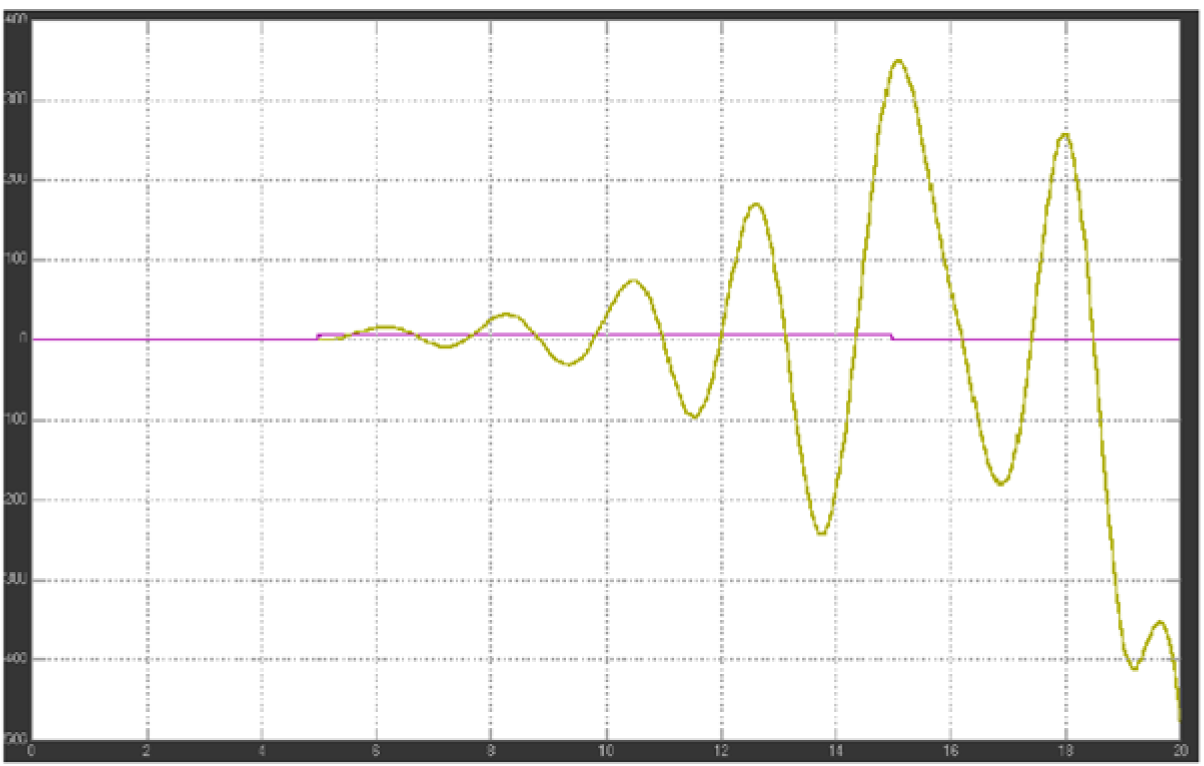


Figure 69: Roulis: P=1, Td=0

With proportional-derivative correctors on all three angles, it is possible to stabilize the drone (figure 64). The system is naturally precise, so it is not necessary to add an integral term. The proportional term allows the response time of the system, its speed but generates oscillations that can be corrected with the derived term.

We tried to get the fastest possible answers for a maximum overshoot of 20%. With the correctors explained in Figure 6.9, maximum over shootings of 15%, 10% and 17% respectively are obtained for pitch, roll and yaw.

The response times at 5% are of the order of one second for the pitch and the roll and of two seconds for the yaw.

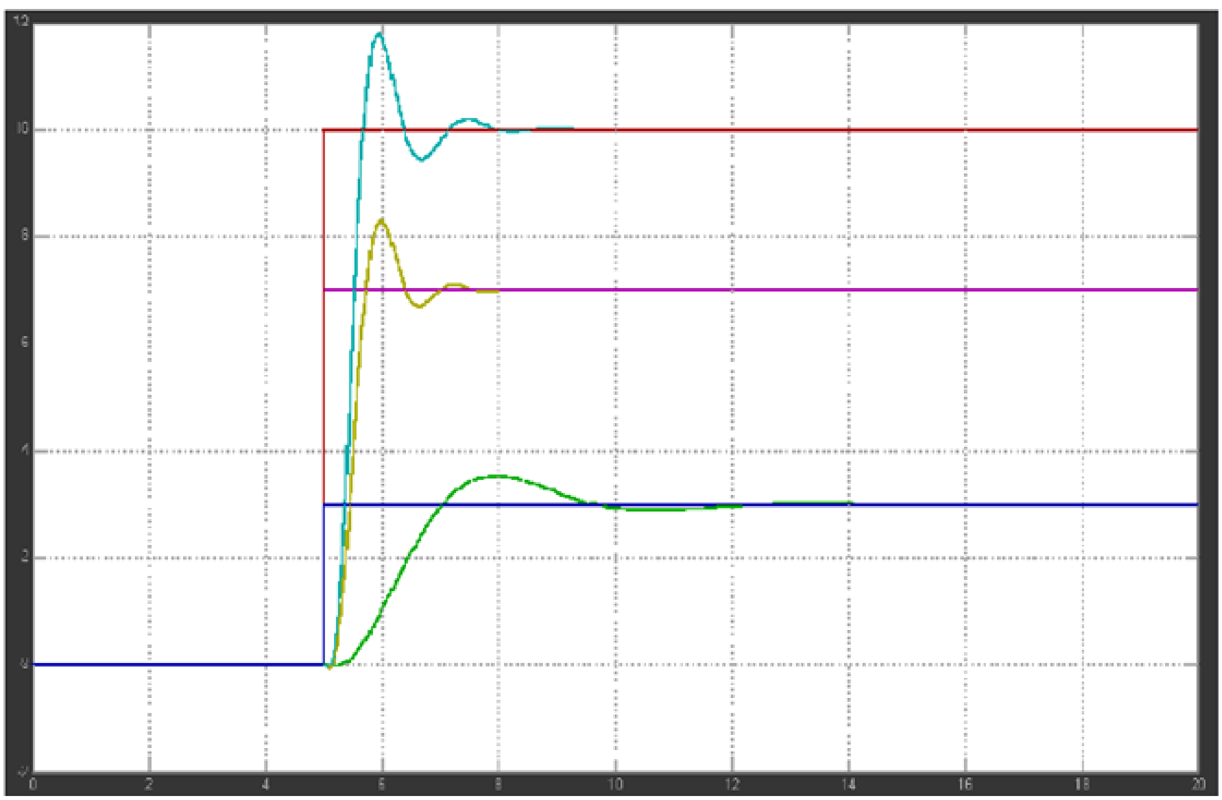


Figure 70: Lacet: P=12, Td=10, Tangage: P=1.5, Td=0.5, Roulis: P=1.5, Td=0.5

2.6. Realisation

2.6.1. Stabilization using Arduino Microcontroller

The measurement of roll, pitch and yaw angles is made using a low-cost AHRS (Attitude and Heading Reference System), which is integrated by accelerometers, gyroscopes, and magnetometers. The AHRS used is the 9DOF Razor IMU which gives the angle information through a serial interface using a data package with a specific and simple-to-decode frame.

Data transmission between the quad copter and the land station (Android application) is made through a wireless link using Bluetooth module HC-05..

The program in the microcontroller consists of three blocks: the main block, and two interruption blocks triggered by a serial reception of the AHRS and the land station (Android application). During the AHRS serial interruption, the package is read, and Euler angles, are stored for further processing and filtering in the main program. In the serial interruption triggered by the android application, the settings and calibration data is read to be processed later. The main block of the program is also composed by several algorithm blocks as shown in Fig 65.

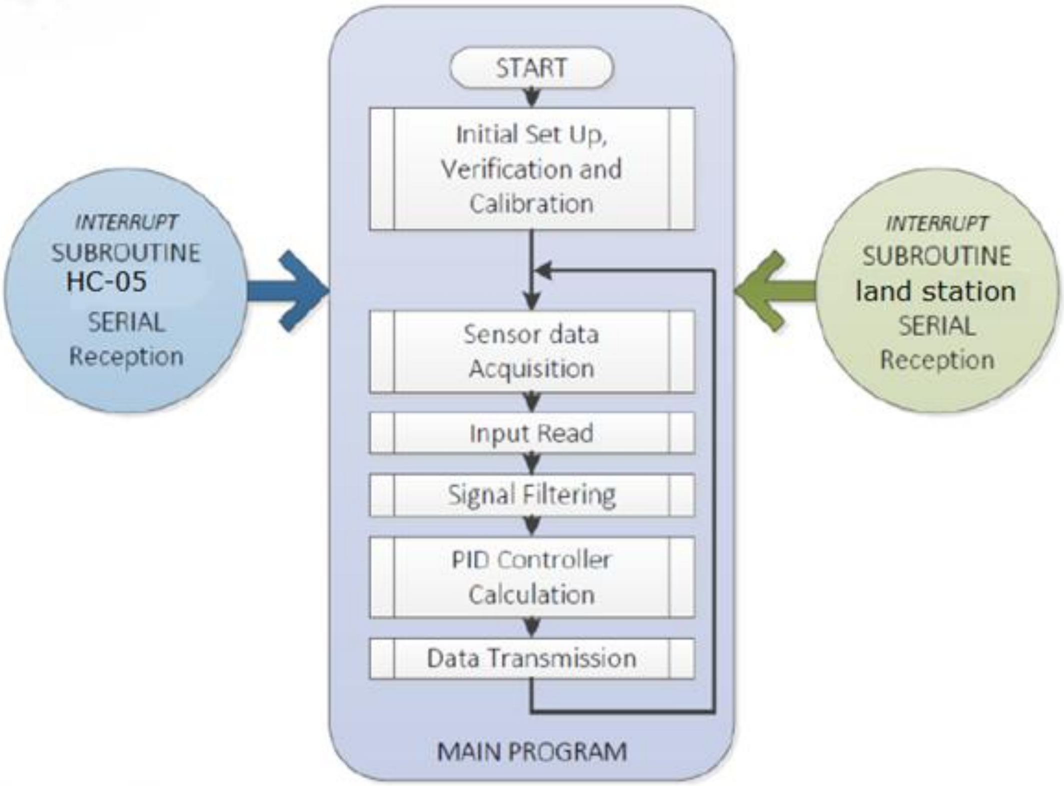


Figure 71: Algorithm blocks

2.6.2. PID Implementation

The aim of PID controllers is to keep the input of gyro angular rate the same as input of the receiver as explained here

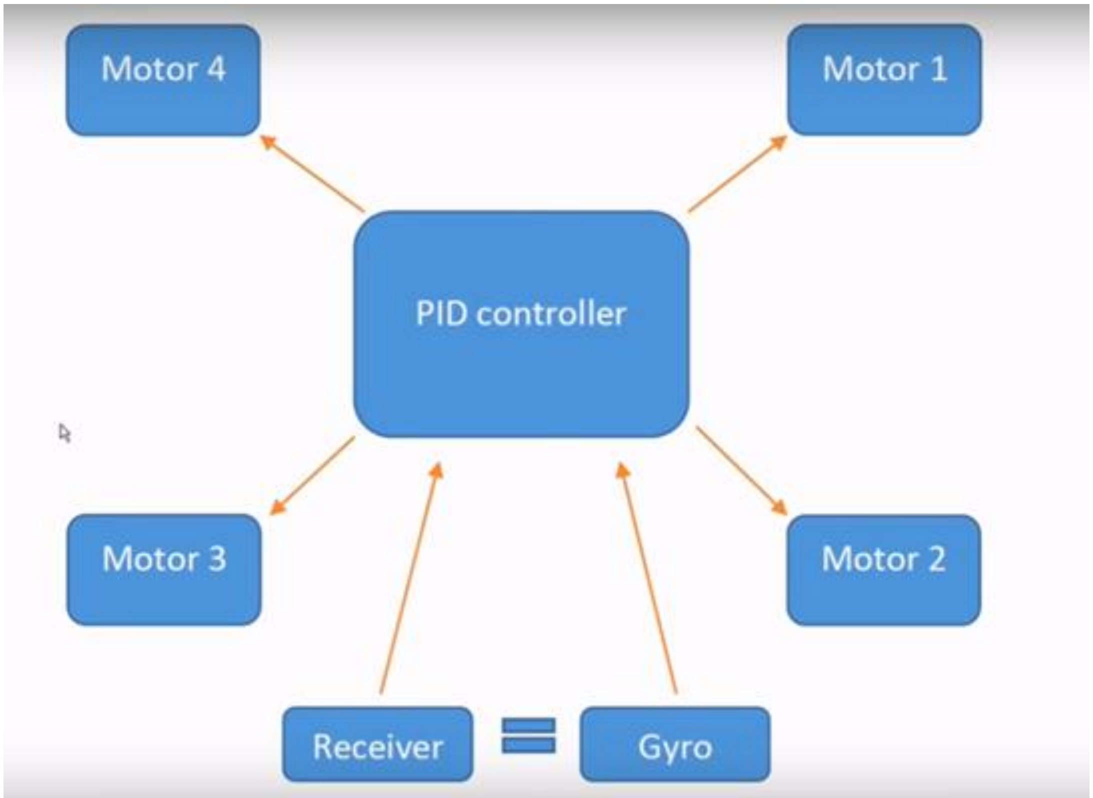


Figure 72: PID Implementation

2.6.3. PID Loop

In order to compensate voltage drop PID corrections must be calculated in this order:

- READ THE GYRO ANGULAR DATA
- CALCULATE THE PID CORRECTIONS
- CALCULATE THE PULS FOR EVERY ESC
- COMPENSATE EVERY PULSE FOR VOLTAGE DROP
- SEND THE CALCULATED PULSES TO THE ESC'S

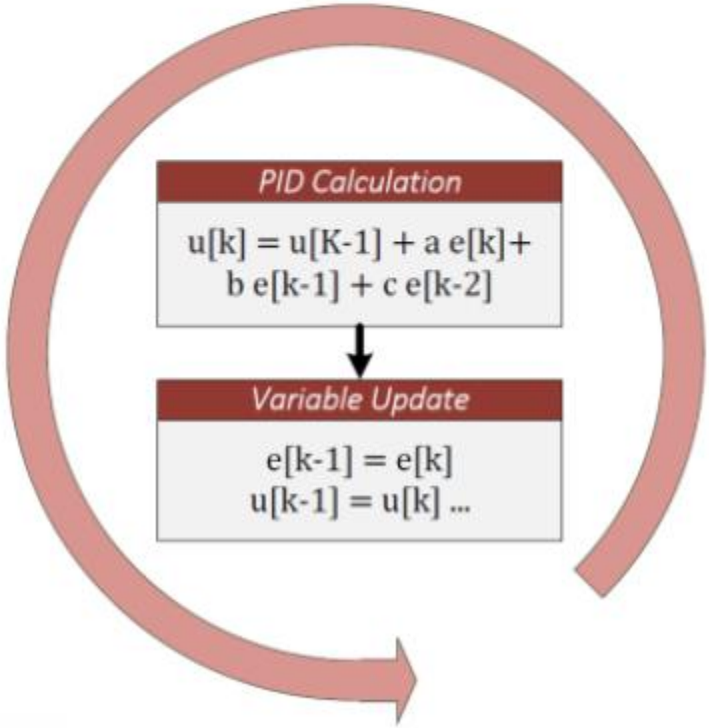


Figure 73: PID Loop

During the system set up, some subroutines are executed to verify the status of sensors and to correct errors to avoid further problems in flight.

Once the system is started, the microcontroller is waiting to receive data from the AHRS or the Android application. The AHRS is set to transmit angle data with a fixed frequency of 50Hz, so when data is received, the control loop is executed at the same frequency to synchronize operations. The control loop first processes the data received from the AHRS, than read measures of inputs from the Bluetooth receiver. Afterwards, all signals are filtered to remove the noise produced mostly by the aircraft's vibration. After the signal filtration, the PID outputs are computed, and finally, the data transmission subroutine is executed.

In every control loop, the filters and PID controllers are computed, and afterwards the variables are updated

2.6.4. Code implementation

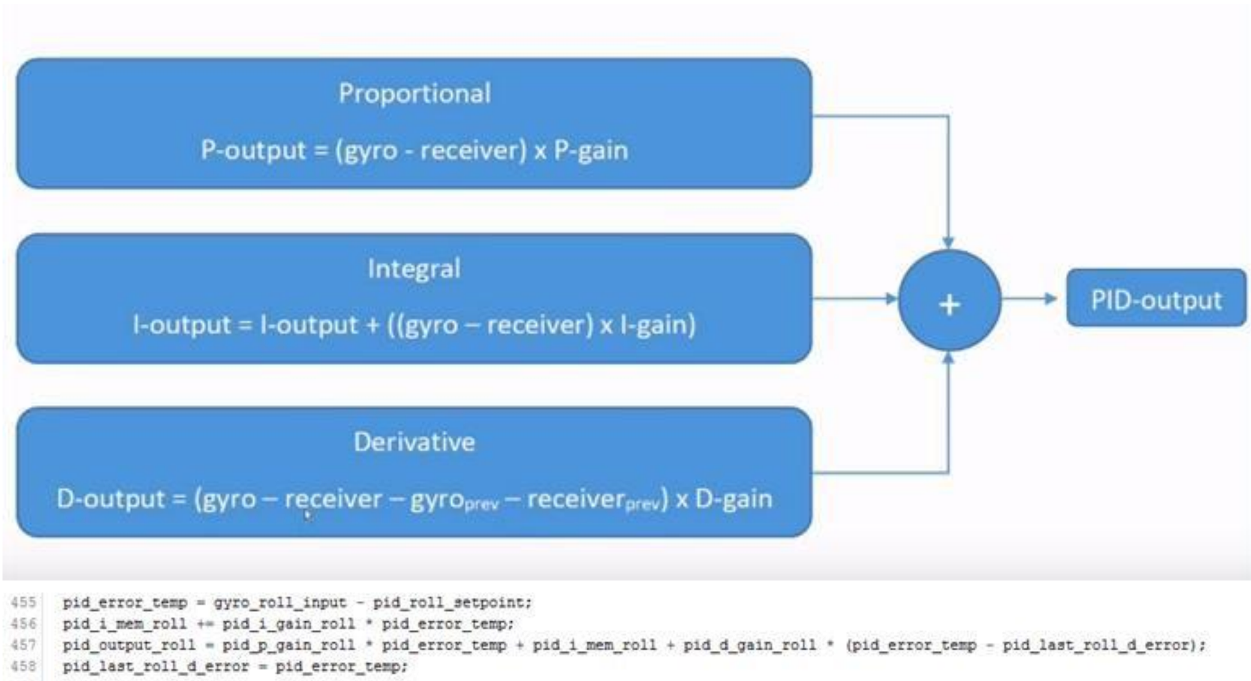


Figure 74: Code implementation

2.7. Synthesis

PID controllers are capable of stabilizing a complex system such as the quadcopter; however, the influence of intense and long external disturbances affects the behavior of the controller.

The actual gains of the PID controllers differ from the original design gains because the math model does not consider with exactitude all the effects acting on the quadcopter like the vibrations or the oscillations of the system. Despite the nature of the system, whose behavior is practically a double integrator, it has a steady state error, which is why the integral gains of all four controllers had to be increased to obtain an improved response. Derivative gains were strongly reduced due to the mild oscillation of the aircraft because its effect produces unstable control signals, which also produce unstable behavior in the system.

Conclusion and perspectives

This section discusses the results of the project. All information here is repeated from earlier sections of this report. With the supervision of M.Ismail AIT MELLAL. The quadcopter kit was chosen and the components were interfaced, tested, and verified to be working properly. We proceeded to making a detailed analysis of specification and requirements, as well as a system modelization where we designed parts of the system. In order to stabilize the drone tuning was done on the PID controllers using custom test benches, automatic PID tuning in Simulink, in addition to using Arduino microcontroller. An iner-drone communication was set and executed successfully.

During this project we encountered many difficulties: the trajectory algorithm that needed more time to develop and implement, the model needed debugging and the gyroscope calibration was problematic due to the fact that it wasn't compatible with the Arduino.

To improve the system behavior, in future works, the implementation of non-linear controls can be made, which would be based on a non-simplified model, allowing wider ranges on roll and pitch angles.We also hope to reduce energy consumption and optimize the code using embedded C language instead.

This project required members not only to interface and program the components of the quadcopter, but also exposed them to mechanical components and reality of project management to accomplish the project objectives.

Ressources

https://www.arduino.cc/en/Reference/HomePage

http://jeromeabel.net/ressources/xbee-arduino#toc21

http://www.supinfo.com/articles/single/1622-module-xbee-avec-arduino

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http://www.ardumotive.com/how-to-use-xbee-modules-as-transmitter--receiver-en.html

https://www.rcgroups.com/forums/showthread.php?731680-Understanding-the-BEC-and-LVC-features-of-your-Electronic-Speed-Control

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http://www.majordome-video.com/guides/le-guide-ultime-de-la-batterie-lipo/