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**By** :

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**THEME**

# Simulation of Quadcopter Motors Responses Stabilized using PID Controller

*Publicly supported ahead of a jury composed of:*

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## ملخص

المركبات الجوية بدون طيار أو الدرون هي مركبات قادرة على اداء مهمة ذاتيا بشكل أو بآخر. يتم استخدامها في العديد من التطبيقات العسكرية والمدنية. ومع ذلك، لا يزال استخدام الطائرات بدون طيار محدودًا بسبب اللاخطية العالية الموجودة في نموذجها الديناميكي. في هذه الأطروحة، سيتم عرض النمذجة الفيزيائية للطائرة رباعية المراوح. بالإضافة إلى ذلك يتم التحكم فيها بواسطة وحدات التحكم النسبي، المتكامل، المشتق المطبقة على محركاتها الاربع من نوع محرك بدون فرش لمقارنة ادائها. يتم تنفيذ نتائج المحاكاة باستخدام رسم بياني وظيفي على برنامج ماتلاب/سوميلينك الذي ينمذج الطائرة رباعية المراوح. في الاخير، سيتم إجراء العديد من الاختبارات على الطائرة بدون طيار من أجل استخدامها في التجارب التطبيقية في الواقع.

***الكلمات المفتاحية:*** الطائرة رباعية المراوح، وحدات التحكم (النسبي، المتكامل، المشتق)، الاستقرار، محركات بدون فرش.

## Abstract

Unmanned Aerial Vehicles (UAVs) or drones are vehicles capable of carrying out a mission more or less autonomously. They are used in several military and civilian applications. However, the use of drones remains limited because of the high nonlinearity presented in their dynamic model. In this dissertation, the modeling of the physics of the quadcopter will be presented. Moreover, the control of the quadrotor is done by conventional PID controllers applied to its four brushless motors in order to compare its performance. Simulation results are performed using a MATLAB/Simulink block diagram that models the quadcopter. Finally, several tests will be done to the quadcopter in order to use them in realization experiments.

***Key-words:*** Quadcopters, PID controllers, stability, brushless motors.

## Résumé

Les véhicules aériens sans pilote (VAP) ou drones sont des véhicules capables d'effectuer une mission de manière plus ou moins autonome. Ils sont utilisés dans plusieurs applications militaires et civiles. Cependant, l'utilisation des drones reste limitée en raison de la non-linéarité élevée présentée dans leur modèle dynamique. Dans cette mémoire, la modélisation de la physique du quadricoptère sera présentée. De plus, le contrôle du quadrirotor se fait par des contrôleurs PID conventionnels appliqués à ses quatre moteurs sans balais afin de comparer ses performances. Les résultats de la simulation sont effectués à l'aide d'un schéma fonctionnel MATLAB / Simulink qui modélise le quadricoptère. Enfin, plusieurs tests seront effectués sur le quadricoptère afin de les utiliser dans des expériences de réalisation.

***Mots-clés:*** Quaqricoptère, contrôleurs PID, Stabilité, Moteurs sans balais.

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## Dedication

*I dedicate this modest work to the people who they are the most expensive,*

*I quote:*

*My parents in the first place, the mother and the father, may God protect them.*

*My two dear sisters, imane and douaa.*

*My dear grandfathers May God forgive them, My dear grandmothers and all my family specially my aunts Sennia, Fatima, Malika and my cousins Walid, Houssem.*

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*LAHDEB Abdelkader*

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# List of Abbreviations

| | | |
|---|---|---|
| ABS | : | Acrylonitrile butadiene styrene |
| ARF | : | Almost Ready to Fly |
| BAC | : | Battery Eliminator Circuit |
| BNF | : | Bing-N-Fly |
| CD,ROM | : | Compact Disc Read Only Memory |
| CW,CCW | : | Clock Wise , Counter Clock Wise |
| DC | : | Direct Current |
| ESC | | Electronic Speed Controller |
| FPV | | First Person View |
| GCS | | Ground Control Station |
| GPS | | Global Positioning System |
| LDR | | Light Decreasing Resistance |
| MEMs | | Micro-ElectroMechanics system |
| MRAC | : | Model Reference Adaptive Control |
| PID | | Proportional,Integrative and Derivative control |
| RC | | Remote Control |
| RC | | Radio Control |
| RMF | | Rotation Magnetic Field |
| rpm | | otation Per Minute |
| RTF | | Ready To Fly |
| SMC | | Sliding Mode Control |
| UAS | | Unmanned Aerial Systems |
| UAV | | Unmanned Aerial Vehicls |
| WI-FI | | WIreless FIdelity |

# Liste of Acronymes

$\varepsilon$ : Absolute linear position of the quadcopter is defined in the inertial frame
$\theta$ : Pitch angle (the rotation of the quadcopter around the $y-axis$)
$\phi$ : Roll angle (the rotation of the quadcopter around the $x-axis$)
$\psi$ : Yaw angle (the rotation of the quadcopter around the $z-axis$)
$\eta$ : Angular position, is defined in the inertial frame
$q$ : Linear and angular position vectors
$V_B$ : Linear velocities in the body frame
$\upsilon$ : Angular velocity in the body frame
$R_{Rot}$ : Rotation matrix from the body frame to the inertial frame
$W_n$ : Transformation matrix for angular velocities from the inertial frame to the body frame
$G$ : Vector of the gravity
$g$ : Gravity
$T$ : Thrust motor on the quadcopter (in the body frame)
$T_B$ : Total thrust on the quadcopter (in the body frame)
$I_n$ : Inertia matrix (diagonal matrix)
$\tau$ : Motor torque
$I$ : Input current
$I_0$ : No load current
$k_t$ : Torque constant
$P$ : Consumed power
$V$ : Voltage drop across the motor
$R_m$ : Motor resistance
$\omega$ : Motors angular velocity in the inertial frame
$k_v$ : Constant of RMF generated per rpm.
$\upsilon_h$ : Air velocity
$\rho$ : Density of the surrounding air
$A$ : Swept area by the rotor
$F_D$ : Frictional force
$k_d$ : Frictional constant
$A$ : Reference area (propeller cross-section, not area swept out by the propeller)
$C_D$ : Dimensionless constant
$R$ : Radius of the propeller
$b$ : Appropriately dimensioned constant
$\tau_D$ : Torque due to drag
$\tau_z$ : Complete torque about the $z$ axis for the $i^{th}$ motor
$\tau_\theta$ : Pitch torque

$\tau_\psi$ : Yaw torque

$\tau_\phi$ : Roll torque

$L_D$ : Distance from the center of the quadcopter to any of the propellers

$I_M$ : Moment of inertia about the motor $z$ axis

$k$ : Appropriately dimensioned constant

$E_{trans}$ : Translational energy

$E_{rot}$ : Rotational energy

$E_{pot}$ : Potential energy

$f$ : Linear external force

# General Introduction

Nowadays , aviation has become an essential element in contemporary life by playing an effective role in the field of air transport for individuals and goods, and it is also a standard of strength in the military field from which it appeared and was developed in it, like all sciences such as medicine, communications, etc.

In the beginning, planes was made traditionally relied on simple principles and their control was close to any the presence of human element 'the pilot' is forced to do the manual control of its trajectory, speed, and altitude. With the novelty of science, today there are what are known as aircraft without pilot or drone, and they are either self-driving and controlling or semi-autonomous, the main objectives of which are the same as the objectives of the primitive aircraft that we will mention later.[2-4]

Unmanned Aerial Vehicles ( UAV's) are autonomous flying machines whose lift and propulsion are ensured by the rotation of the motors. These aircraft are capable of following a trajectory, navigating space, using visual navigation, taking off, flying and landing vertically, performing near-stationary flights and low-level great maneuverability [9].

Research in the field of autonomous air vehicles is essentially multidisciplinary. Indeed, it involves a wide variety of areas such as aerodynamics, signal and image processing, automatic control, mechanical, composite materials and real-time computing.

Several types of UAV's can be found, among them the Quadcopters.

They are semi-autonomous and controlled plane consisting of four brushless type electric motors and an electronic card to control the motors in addition to a structure that carries these vehicles made of a lightweight material [13] so that the weight of each plane is less than the opposing motors so that it can rise from The earth's surface. However , the main problem for quadcopters is to maintain their stability .

In this dissertation, we are particularly interested in air vehicles and more particularly to the mini quadcopters . They are among the most complex of flying objects, because their flight dynamics is inherently nonlinear, and the variables are strongly coupled. The quadrotor has the ability to hover, which is required in some applications.

The main objective is to develop a dynamic model of this quadrotor that will serve as a basis for a control PID (Proportional ,Integrator,Derivative) approach to regulate the position of equilibrium (hovering) and the stability of the quadcopter.

This dissertation is structured as follows ,

**In chapter 1,** the main definitions , types and the main components of quadcopters are given in detailed way. The objective is to understand the field of quadcopters in order to understand them more .

**In chapter 2,** a full discerption of the main components of quadcopters ‘ the brushless motors ‘ is given. The principal working of these motors as their modeling is viewed . Moreover, for quadcopter stability , the mathematical modeling of the quadcopters is also given .

**In Chapter 3,** a full review of dynamic quadrotor model control is given, based on more advanced literature references. For stabilization purpose, proportional integral derivative (PID) controller is applied. The results are tested in simulation using Matlab/Simulink The choose of optimal PID values is discussed and they are implemented in the constructed quadcopter.

At the end of this work, a general conclusion is then given as well as some recommendations for the present work and the future developments.

# Chapter 1

# Basics of Quadcopters

## 1.1 Introduction

Drone technology is constantly evolving as new innovation and big investment are bringing more advanced drones to the market. They are used for different purposes such as military services , agriculture field and others. However , before using them , a well known knowledge of their history and types as well as their components is needed . Hence , in this chapter , a full stat of the art of drones, components and their principal working is viewed.

## 1.2 Definition of drone

A drone, in technological terms, is an unmanned aircraft. Drones are more formally known as unmanned aerial vehicles (UAVs) or unmanned aircraft systems (UASes). Essentially, a drone is a flying robot that can be remotely controlled or fly autonomously through software-controlled flight plans in their embedded systems, working in conjunction with onboard sensors and GPS [1].

## 1.3 History of drone

The reason for thinking about making the drone was the fall of the American spy plane (U-2) 1960 over Russia and the Cuban missile problem 1962 where the first pilotless vehicles were built during the First World War. These early models were launched by catapult or flown using radio control. To understand more about this , in what follow , we will focus only on the recent drones from the last decade [2].

- In January 1918, the US Army started production of aerial torpedoes. The model that was developed, the Kettering Bug, was flown successfully in some tests, but the war ended before it could be further developed. But the real first pilotless in the history is Ruston

Proctor Aerial Target winged aircraft. It was a radio-controlled pilotless airplane, based on RC technology from the inventor Nikola Tesla in 1917 [3-4].

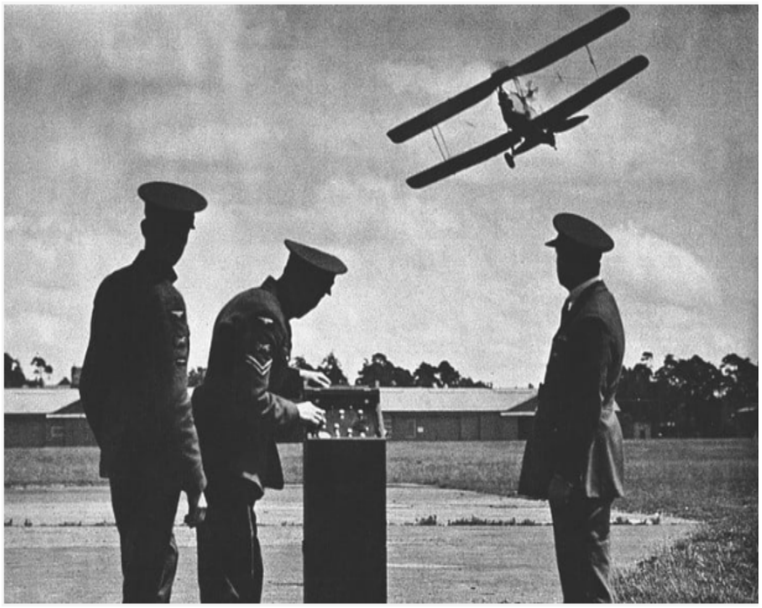

Figure 1.1: Ruston Proctor Aerial Target winged aircraft [5]

- In 1917, First drone scientific experiments in England as it was developed in 1924 as mobile targets for artillery and during the inter-war period the development and testing of unmanned aircraft continued [6].
- In 1935, the British produced a number of radio-controlled aircraft to be used as targets for training purposes. It's thought the term 'drone' started to be used at this time, inspired by the name of one of these models, the DH.82B Queen Bee. Radio-controlled drones were also manufactured in the United States and used for target practice and training [7].
- In October 1973, it was practically used for the first time in the Vietnam War and began to be used in a range of new roles, such as acting as decoys in combat, launching missiles against fixed targets and dropping leaflets for psychological operations and it was used too in the October 1973 war, but the required result was not achieved in the last due to the weak capabilities at the time and the presence of the Egyptian missile wall. and then she knew its first effective participation in the battle of the Bekaa Valley between Syria and Israel, which resulted in the fall of 82 Syrian plane without any Israeli plane crashing [8]. Following the Vietnam War other countries outside of Britain and the United States began to explore unmanned aerial technology. New models became more sophisticated [7], with improved endurance and the ability to maintain greater height. In recent years models have been developed that use technology such as solar power to tackle the problem of fueling longer flight [9].

- Nowadays , drone models are very developed and have wide use, even on the civilian side as they have many functions, ranging from monitoring climate change to carrying out search operations after natural disasters, photography, filming, and delivering goods. But their most well-known and controversial use is by the military for reconnaissance [10], surveillance and targeted attacks.
  Since the 9/11 terrorist attacks, the United States in particular has significantly increased its use of drones. They are mostly used for surveillance in areas and terrains where troops are unable to safely go. But they are also used as weapons and have been credited with killing suspected. Their use in current conflicts and over some countries has raised questions about the ethics of this kind of weaponry, especially when it results in civilian deaths, either due to inaccurate data or because of their proximity to a 'target' [11].

Figure 1.2: Kettering Bug [12]

## 1.4 Types of drones

Drones can be classified in different types , the flowchart bellow will give a summarize of all existing drones;

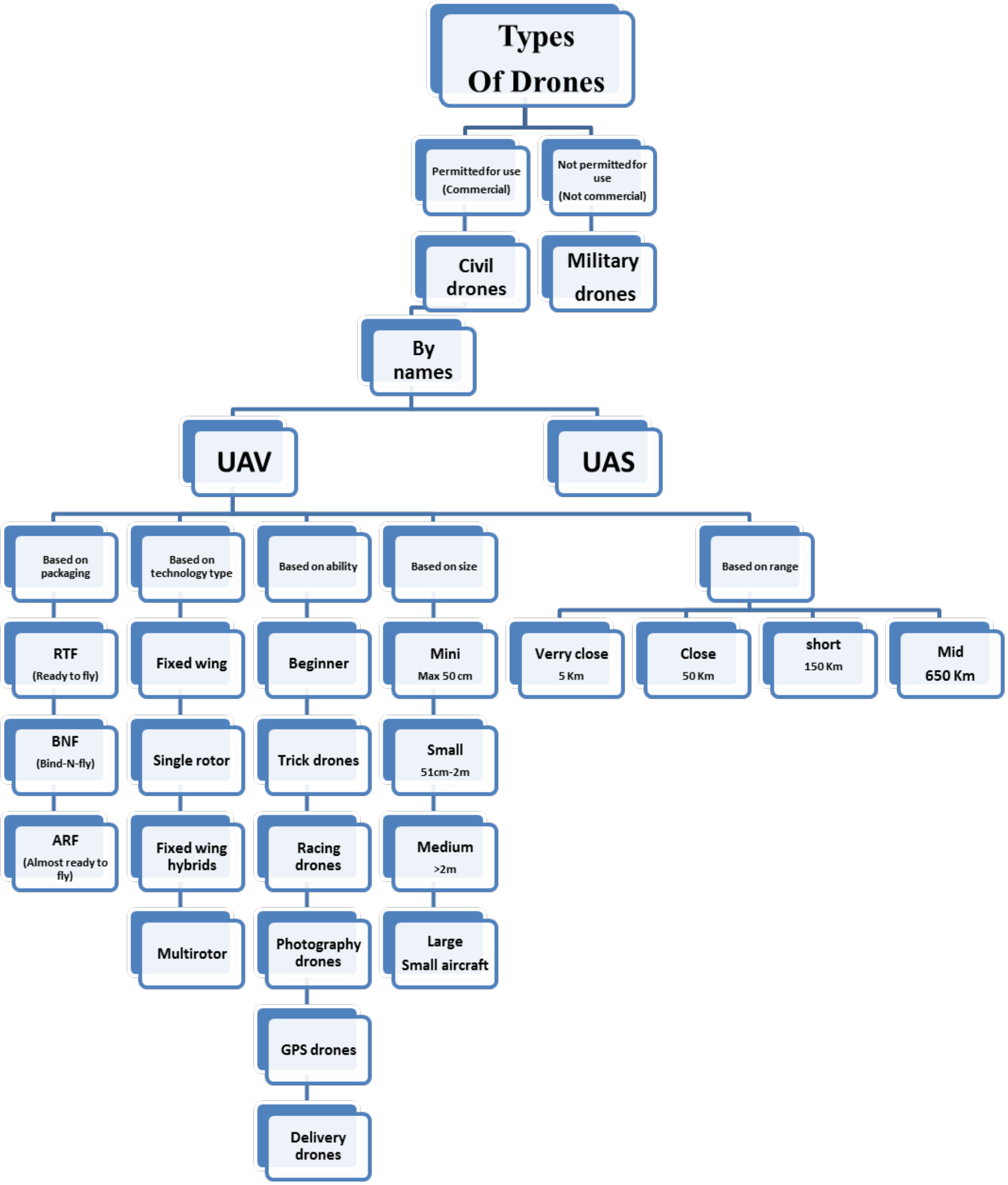

Figure 1.3: Types of drones [13]

To clarify the development of the drone over time, we decided to create a table that contains the differences in terms of shape, size and capacity.

Frame

Table 1.1: Characteristics of new UAV's

| | Primary UAV's | Develloped UAV's |
|---|---|---|
| | Large size | Small |
| Materials | Havey/Not rigid | Lightweight/Rigid |
| Electrical Power | Batteries | Baterries,Solar energy [8] |
| Autonomy | Verry limited missions | Verry considerable missions |
| speed | Max 80 km | Max 402km/h (2020) |
| motors | Microturbines (Diesel ) | Brushless motors |
| Accessories/functions | Army | Army/Photography/Delivery |

Table 1.2: Development of the drone over time

| | In 2018 | In 2020 |
|---|---|---|
| Weight | 512 kg | 320 g |
| Dimensions | Wingspan: 14.84m,Length: 8.23m, Height 2.21m | 24.4*6.7*6.5 cm |
| Material | / | Plastic ABS |
| Autonomy/Max speed | 14 hours / 217 km/h | 25 mn / 15 m/s |
| control | Radio (GCS) | WI-FI |
| Form and type | Army use | Civil use |

## 1.5 Multicopters

### 1.5.1 Definition

We tell the term multi for any sum more than two. And rotor is the dynamic part of the motor, Copter is a motor with propeller together what gives a rotational movement result a raiser and mover forces transfer the body (motor + propeller +accessories) to a certain height and distance to do a required mission. The value of this force relates to the speed of motor and the size of the propeller.

Scientifics call this name to a small and simple aircraft contain three copters or more with a special frame and control equipements. All this form an electromechanical system semi-autonomous driven by a remote control.

Multicopters are aerodynamically unstable and absolutely require an on-board computer (autopilot) for stable flight. As a result, they are " Fly by Wire " systems and if the computer isn't working, you aren't flying. The autopilot combines data from small on-board MEMs technically called sensors (gyroscopes, accelerometers ..) to maintain an accurate estimate of its orientation and position and to give a precise error values for doing a best elimination of the disturbance mean to make our system always stable [11].

Physically, the multi-rotor has six freedom degrees on the axes (X,Y,Z) what mean that he can moves on three trends called throttle ,roll, pitch and yaw respectively without forget his spin around himself.

## 1.5.2 Flight dynamics of multicopter

### 1.5.2.1 Altitude

Pratically, increasing the speed of all the motors at the same time with the same value result a height move on the Z axis.

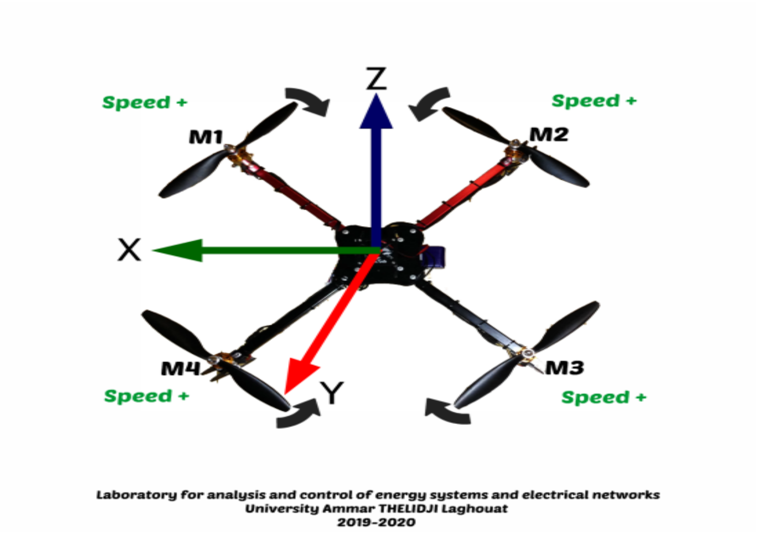

Figure 1.4: Altitude movement

### 1.5.2.2 Roll

Rotation around the side-to-side axis is called Roll. Pratically, the reducation of two front or rear motors result a roll movement.

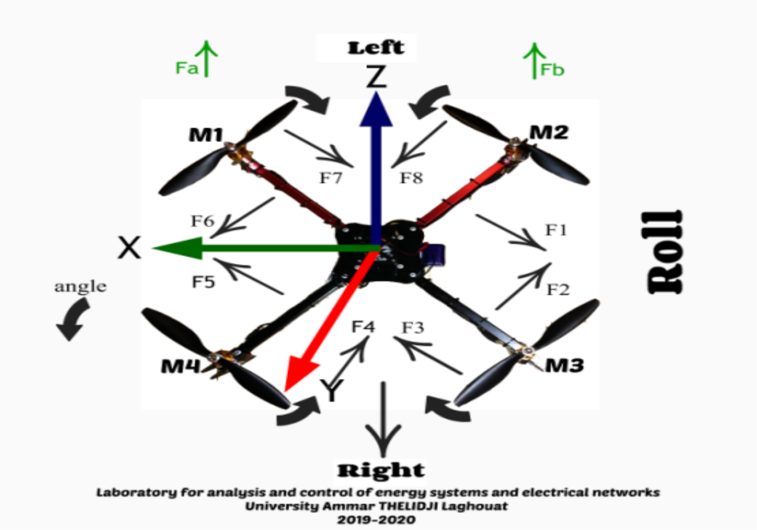

Figure 1.5: Roll movement

#### 1.5.2.3 Pitch

Rotation around the front-to-back axis is called pitch. Practically, the reducation of the speed of two motors on the right or two motors on the left results a pitch movement.

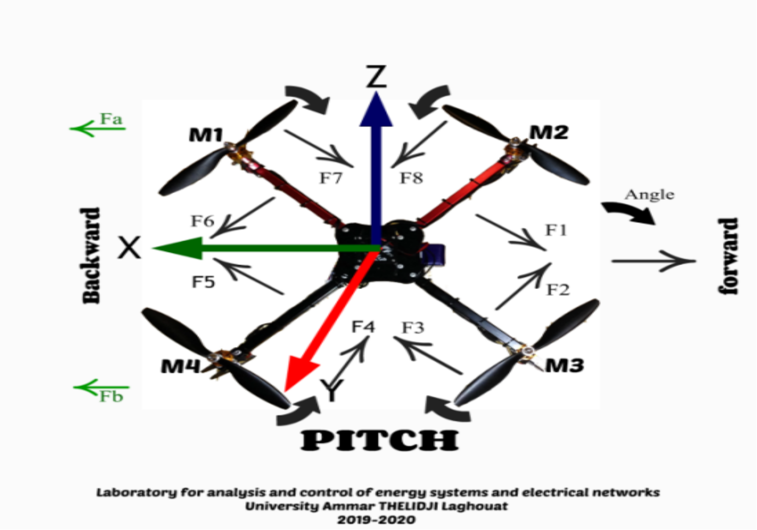

Figure 1.6: Pitch movement

#### 1.5.2.4 Yaw

Rotation around the verticle axis is called Yaw. Pratically, reducation of the speed of two opposite motors with rising of the speed of the other two motors make the quad rotate around itself ( spin ) that result a YAW movement.

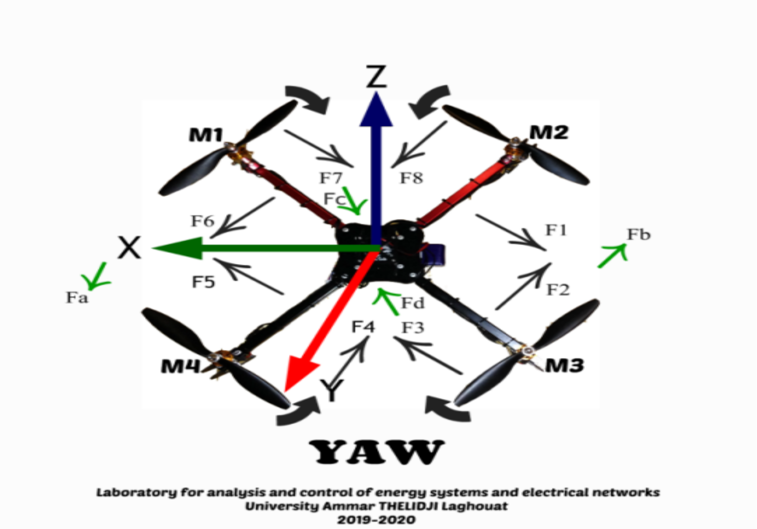

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Figure 1.7: Yaw movement

### 1.5.3 Types of multicopters

Multi-copters (as known as multirotors) often use fixed-pitch propellers, so the control of vehicle motion is achieved by varying the relative speed of each motor. Radio controlled multicopters are increasingly popular for aerial photography, and land surveying. And more recently racing drones, where multi-copters are used in racing and free-style competition.
There are many types of multirotor. They are generally categorized by the number of motors used, for example a three-motored multi-copter is a called a tricopter, and the configuration can also be referred to as Y3. In this post we will discuss the following types of multirotors [14].

1. **Bicopter;**
2. **Tricopter (Y3, T3) ;**
3. **Quadcopter (X4, Y4, V-Tail, A-Tail);**
4. **Pentacopter;**
5. **Hexacopter (Y6);**
6. **Octocopter (X8).**

#### 1.5.3.1 Bicopter

Bicopter could be the cheapest multi-copterconfig to build among all because it only uses two motors and two servos. But it's also the most difficult platform to stabilize in flight. It has the least lifting power given the fact that it only has 2 motors [8] . Bicopter is not a very popular configuration for hobbyists [15].

Figure 1.8: Bicopter [16]

#### 1.5.3.2 Tricopter

The Tricopter has 3 motors, and typically in a “Y” shape, where the arms are usually 120 degrees apart. Tricopters can sometimes be found in a “T” shape too. Two propellers on the front arms spins the opposite direction to counter each other out. The rear motor can be tilted left and right by a servo to enable the yaw mechanism. It’s a popular yet relatively cheap configuration because it only requires 3 motors, although you also need an additional servo but they are generally cheaper than brushless motors.

Generally speaking, tricopters are less stable than other multirotors with more motors, and it’s not as robust due to the vulnerability of the tail servo and mechanics in crashes. For hobbyists, it’s also harder to build because of the yaw mechanism. Tricopter has more yaw authority comparing to a quadcopter. What that means is when a quadcopter or hexacopter yaws, they do so by slowing down half of the motors and speeding the other half. If the copter is already at full speed (all motors at 100%), it will have to lower the speed to make yaw happens.

However on a Tricopter, it uses a servo to achieve yaw so it loses less thrust when the same situation happens. It also has lower lifting power because of the smaller motor numbers [15].

Figure 1.9: Tricopter [17]

#### 1.5.3.3 Quad-Copter

A quadcopter has 4 motors mounted on a symmetric frame, each arm is typically 90 degree apart for the X4 config. Two motors rotate CW (clockwise), and the other two rotate CCW (counter clockwise) to create opposite force to stay balance. Quadcopter is the most popular multirotor configuration, with the simplest mechanical structure.

It's widely used for drone racing in the form of "mini quad". There are 2 main configurations: X or +. X config is more popular as you can keep the propellers out of the camera's view (for FPV and aerial filming). Some people fly the plus (+) config because it's more intuitive, and flies like an airplane. It'seasier to figure out the orientation.

There is also the H configuration, which allows a camera to be placed on the frame well forward to avoid having propellers in the view of the camera. There are always debates about whether X or H are better, especially in the mini quad community [15].

Figure 1.10: Quadcopter [18]

#### 1.5.3.4 Y4 motors

It looks like a tricopter but without the tail servo. There are two normal propellers and motors in front on separate arms and two coaxial motors in the rear mounted to one arm. Mechanically it's simpler than tricopters because of the absence of the and yaw mechanism.

While they weigh almost the same they have about 1/3 more lifting power than tricopters. They are usually more reliable than Tricopters because there are no potential servo issues [15].

Figure 1.11: Y4 copters [19]

#### 1.5.3.5 V-Tail and A- Tail motors

The V-Tail and A-Tail are basically quadcopter config with the front motors on normal quadcopter arms, while the rear motors located in close proximity, tilted at an vertical angle either inward or outward. It's a mix between a quadcopter and a tricopter and very similar to Y4 config.

This is not a popular configuration because it gives lower power efficiency (air flow interference at the tail motors). However V-Tail/A-Tail certainly looks awesome and provides a better orientation visibility. [15]

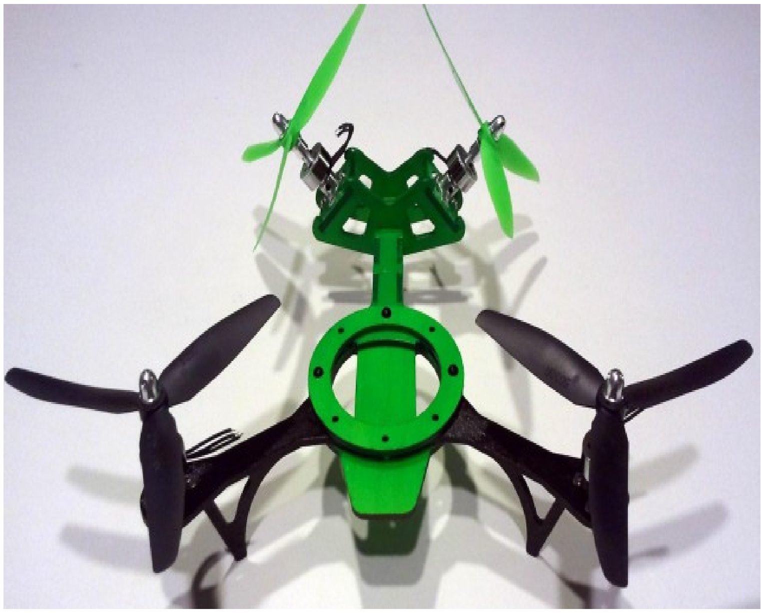


Figure 1.12: V-Tail and A-Tail [20]

#### 1.5.3.6 Pentacopter

There isn't much information on this config because it's not a popular setup. But there have been people building this and verified the feasibility of this cool looking config. One obvious advantage of the pentacopter is the wide angle of the two front arm which allows the propellers to stay out of the camera view as far as possible [15].

Figure 1.13: Pentacopter [21]

#### 1.5.3.7 Hexacopter

The hexacopter has 6 motors mounted typically 60 degree apart on a symmetric frame, with three sets of CW and CCW motors/propellers.
Hexacopters are very similar to the quadcopters, but they provide more lifting capacity with the extra motors. There is also improvement in redundancy: if one motor fails, the aircraft can still remain stable enough for a safe landing. The downside is that they tend to be larger in size and more expensive to build [8][15].

Figure 1.14: Hexacopter [22]

#### 1.5.3.8 Y6 Hexacopter

The Y6 has 6 motors on a “Y” shape frame. They are similar in shape to a tricopter but it has two motors on per arm, one above and the other. It uses both CW and CCW propellers on the same arm rather than a servo to enable yaw.

This type of multi-copter can be made really compact (similar size to a tricopter), but with similar lifting capability as a hexacopter. However Y6 config is less efficient due to the coaxial motor arrangement [15].

Figure 1.15: Y6 Hexacopter [23]

#### 1.5.3.9 Octocopter

A typical octocopter has 8 motors on the same level with four sets of CW and CCW propellers. Octocopters are similar to quadcopters and hexacopters. It’s like an upgrade version of the hexacopter with even more lifting capacity and redundancy.

However the large number of motors means they draw more current, and you will probably need to carry multiple battery packs. Also it’s going to be expensive. They are very popular as aerial photography platforms and carrying heavy, professional filming gears [15].

Figure 1.16: Octocopter [24]

#### 1.5.3.10 X8 – 8 Motors

An X8 octocopter uses 8 motors that are mounted on four arms, on an “X” shaped frame with four sets of CW and CCW props. Characteristics are similar to the Y6 [15].

Figure 1.17: X8-8 Motors [25]

### 1.5.4 Components of quad-copter:

Quadcopters are compounding in popularity each and every day. This is largely due to their appeal to a wide array of hobbyists including amateur filmmakers, photographers and nature lovers among many others. As a hobbyist, having a basic understanding of the different parts of a quadcopter can help in troubleshooting repairs and can help when you're trying to modify a quadcopter to suit your specific needs.

A quadcopter looks like a complex piece of machinery and it may seem like an intimidating prospect to modify or fix such a thing at home. But the truth is that if you have an understanding of the parts, it becomes much easier. Quadcopter components are designed to come together pretty easily, and if directions are followed, you can actually build a DIY quadcopter at home! [26]

#### 1.5.4.1 Frame

The skeleton of a quadcopter is the frame , some motors and propellers attached to the frame. Quadcopter frames come in a variety of sizes and weight ratings. Most have the same basic appearance – a vague X shape. For hobbyists wishing to mount something with additional weight such as a camera, a sturdier frame rated for more weight is recommended.

However, adding a sturdier material typically creates more weight itself, causing you to require longer propellers and a stronger motor to create the lift necessary to pull up the weight. There's always a delicate balance played by the manufacturers between flight speed, maneuverability, and flight time [26].

Figure 1.18: Quadcopter frame [27]

#### 1.5.4.2 Motor

The next and probably most important component is the motor. Motors are rated in "Kv" units, which equate to the number of revolutions per minute a motor can achieve when a 1v current is introduced to it unhindered. The higher the Kv, the faster the motor can spin.

However, faster is not always better. A faster motor spin requires much more power from the battery, causing your flight times to decrease. More RPMs also decrease the life of the motor over the long run [26].

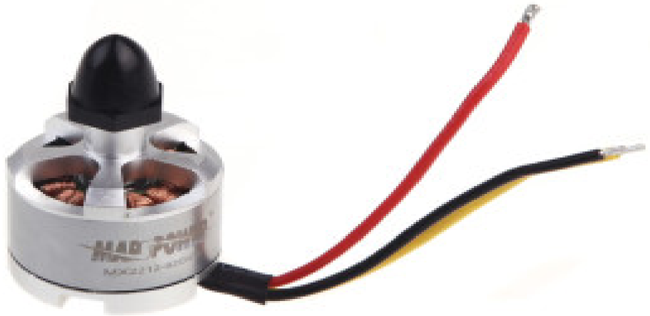


Figure 1.19: Quadcopter motors [26]

#### 1.5.4.3 Propellers

Propellers largely effect the speed at which the quadcopters fly, the load that they can carry, and the speed at which they can maneuver. To affect these various attributes, you can increase or decrease the length of the propellers and the pitch of the propeller. The pitch is the shape and slant of the propeller.

Longer propellers can achieve stronger lift at lower rpm than a shorter propeller, but take longer to speed up and slow down. Beyond a certain size, they're literally unable to fly. For heavier weights, you'll typically see manufacturers add more arms onto the frames (hexacopters/octocopters).

Shorter propellers allow the quadcopter to change speed quickly and do tend to produce better maneuveringcapabilities, however they require more energy to spin them. This causes excess strain on the motors, which may lead to shorter life span for the motors. If you put everything together, an efficient quad will have properly sized, low rpm motors with very large props.

The faster you want to go, the more aggressive a pitch you want. If you want to go somewhere fast a higher pitch might be appropriate. However, since quadrotors are generally hovering this means you want the lowest pitch available. Most quadcopter propeller pitches are typically the same.[26] The Propellers are made of either plastic or carbon fiber, to be light and smooth.

Figure 1.20: Quadcopter propellers [26]

#### 1.5.4.4 Electronic Speed Controller (ESC):

An ESC supplies the proper modulated current to the motors, which in turn produce correct rates of spin for both lift and maneuvering. There are fewer things to consider with an ESC than with other components since they're a fairly standard part, but there are two small factors.

Most ESCs come with the SimonK firmware, which is designed for the precision timing of multiple rotors which a quadcopter uses. This is a standard feature in most ESC designs now. Usually ESCs also come with a battery eliminator circuit, which allows the flight control and transceiver components to connect to the ESC rather than directly to the battery [26].

Figure 1.21: Electronic Speed Controller (ESC) [26]

#### 1.5.4.5 Flight Controller

The flight controller is basically the little computer which controls the craft, and interprets the signals the transceiver sends to guide the quadcopter. For builders of quadcopters, choosing a flight controller is more of a personal choice in many ways, not unlike choosing from various PC processors in the same power range.

Each have various options that each manufacturer wants and may or may not be customizable. If this is something that needs to be fixed, start reading the forums and listen to hobbyists who recommend affordable, reliable controllers which work with most components easily [26].

One of the most developped controllers called Pixhawk, it is an advanced autopilot system of 3DR. if features transparent for hardware and convenient for re-development. Pixhawk integrates with two advanced processor, STM32F103 backup failsafe 32-bit co-processor provides for manual recovery and has its own power supply if controlling any autonomous vehicle.

Users can also adjust the configurations of Pixhawk according to different use and hobbies for different vehicles. In recent years, s one of the cores of autopilot system, Pixhawk has gained a profound popularity among developers and hobbyists for being pratical, easy to handle, economical [27].

Figure 1.22: Pixhawk flight Controller [28]

**Specifications**

- **Processor**

o 32-bit ARM Cortex M4 core with FPU
o 168 Mhz/256 KB RAM/2 MB Flash
o 32-bit failsafe co-processor

- **Sensors**

o MPU6000 as main accel and gyro
o ST Micro 16-bit gyroscope
o ST Micro 14-bit accelerometer/compass (magnetometer)
o MEAS barometer

- **Power**

o Ideal diode controller with automatic failover
o Servo rail high-power (7 V) and high-current ready
o All peripheral outputs over-current protected, all inputs ESD protected

- **Interfaces**

o 5x UART serial ports, 1 high-power capable, 2 with HW flow control
o Spektrum DSM/DSM2/DSM-X Satellite input
o Futaba S.BUS input (output not yet implemented)
o PPM sum signal

o RSSI (PWM or voltage) input
o I2C, SPI, 2x CAN, USB
o 3.3V and 6.6V ADC inputs

- **Dimensions**

o Weight 38 g (1.3 oz)
o Width 50 mm (2.0")
o Height 15.5 mm (.6")
o Length 81.5 mm (3.2")

#### 1.5.4.6 Radio receiver

Radion receiver consists of a component which connects to the flight controller, to receive signals, and a controller to transmit them. There are a lot of very slick receivers which work quite well with standard quadcopter flight controllers. However the key is to be sure that it supports at least four channels if not as high as eight or nine.

A channel is a control input. If your quadcopter had no channels, it would just hover in place. A minimum of 4 channels is required to get the quadcopter to move. 2 channels would be available for each stick on the transmitter. Each additional channel allows you to add controls for accessories (like gimbal control) onto the transmitter.

If you're going to stay with this hobby for a while, then it makes sense to invest in a good transmitter now, something that has up to 8 or 9 channels. [15]

Figure 1.23: Radio receiver [15]

#### 1.5.4.7 Remote control (RC):

A handy programmed tool that transmits remote instructions to drones via radio, Wi-Fi... ect. Containing several locks and some possible moves in the form of codes that express a specific control information in addition to charging batteries also an receiver and sender of instructions and an electronic card to process and read this informations as it can contain a small screen .

Figure 1.24: Remote controller [29]

#### 1.5.4.8 Batteries:

Finally, to power the quadcopter you'll a power source, which is typically a LiPo (Lithium Polymer) battery. LiPo batteries use a C rating, which stands for it's capacity to discharge. You'll typically see a LiPo battery have "20C". So if you see a 25C 4000mAh LiPo battery, it means that you can get a maximum of 25C * 4 = 100A (A standing for Amps).

The power of the battery is usually dictated by the energy draw required from the ESCs. For example if you motor's maximum draw is 19A, at the very least you'll want a 30A ESC to be safe. Now multiply that by the number of propellers you have (4 in this case) and you'll get the maximum draw for your entire quad – 4 * 19A = which is 76A. Your 4000mAh 25C LiPo would definitely be enough for this quadcopter.

A lot of battery types can be fully discharaged, but the LiPos have a minimum voltage requirements, which if gone beyond can cause damage to the battery. In most cases it's 3.0 volts, but can vary from battery to battery. This is generally about 80 – 85% usage of your battery. Once past this mark, battery power drops fairly quickly.

So make sure you're landing or are about to land when you hit this mark. You'll also notice that most quadcopters come with a battery charger specially designed for the battery. It's important to use the one they supply you with. It controls how much current is sent to the battery. Charging a LiPo battery past 100% could actually cause a fire. Make sure to charge batteries in a fire safe area (away from things that are flamable). Allow your battery time to cool before charging again [13].

Figure 1.25: LiPo batteries [13]

## 1.6 Conclusion

In this chapter, a general idea about drones , their history, types and development in terms of shape, size and performance of tasks is viewed . Also , the advantages of each one of each type of drones is given . The basic control equipment of the Quad-copter, such as (Pixhawk, ESC, RC, BATTERIES, GPS..) and the secondary equipment as the photography apparatus etc., and how their weight and their positioning affect on their work and stability is given . The next chapter , will take the second part of quadcopters , which is dedicated to the mathematical modelling as well as control technical of the quadcopters.

# Chapter 2

# Quadcopter Control Methods

## 2.1 Introduction

In any industrial system that contains electrical equipment, we need control systems through which we work to monitor its work and guide it according to our will, such as determining the speed of the motors or the intensity of the necessary current ... etc.

The control of systems in general breaks down into two types. manual control where we can intervene and changing the parameters of the systems (open loop control) but in some cases where we cannot intervene we must use automatic control (closed loop control).

In addition , stability of quadcopters is the main problem facing any related technology. Maintaining the speed of motors to achieve any desired reference is a complicated task . Hence , in this chapter , the mathematical modelling of quadcopters is given . Next , the control methods used for quadcopter stability is viewed.

## 2.2 Mathematical modeling of quadcopter

The knowing of the mathematical modeling of the quadcopter is an essential part to control and stabilize its movement. The modeling consists of defining the structure of the quadcopter, modeling its kinematics, motors , forces , torques and its equations of movement. [30]

### 2.2.1 Frame model

The quadcopter structure is presented in Figure 2.1 including the corresponding an-gular velocities, torques and forces created by the four rotors (numbered from 1 to 4).

The absolute linear position of the quadcopter is defined in the inertial frame $x, y, z$-axes. The angular position, is defined in the inertial frame with three Euler angles ($\eta$). Pitch angle $\theta$ determines the rotation of the quadcopter around the $y - axis$ , Roll angle $\varphi$ determines the rotation around the $x - axis$ and yaw angle $\psi$ around the $z - axis$. Vector $q$ contains the linear and angular position vectors.

$$\varepsilon = \begin{bmatrix} x \\ y \\ z \end{bmatrix}, \eta = \begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix}, q = \begin{bmatrix} \varepsilon \\ \eta \end{bmatrix} \tag{2.1}$$

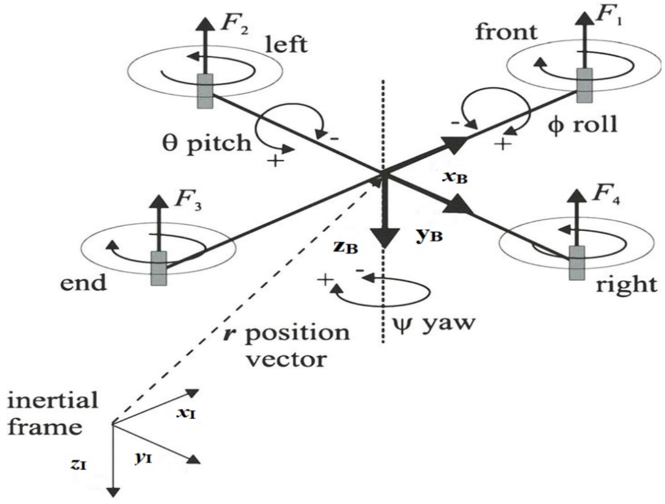


Figure 2.1: Inertial and body frames of a quadcopter [31].

### 2.2.1.1 Yaw, Pitch and Roll angles

### a) Yaw angle

Starting with the Yaw it's a rotation of the head of the quadcopter whether right or left and it could be realized without moving a quadcopter from his hovering position, this kind of movements is frequently seen on Arial photography where the quadcopter stay stationary and turning left and right to capture whether it's a sport event or the any action.

### b) Pitch angle

The pitch is the movement when a quadcopter moves backward and forward. For transition made with a speed changes on the front and rear motors , to pitch forward the rear motor accelerate and those on the front deaccelerate in this case the quadcopter will move formard, then the opposite to go backward.

### c) Roll angle

The roll is a movement just like the pitch but in this case when a Roll movement is needed the quadcopter will dodge left or right.This movement is whether dodging or sliding without any angels changes.
Yaw , Pitch and Roll angles are shown in figure 2.2 [32].

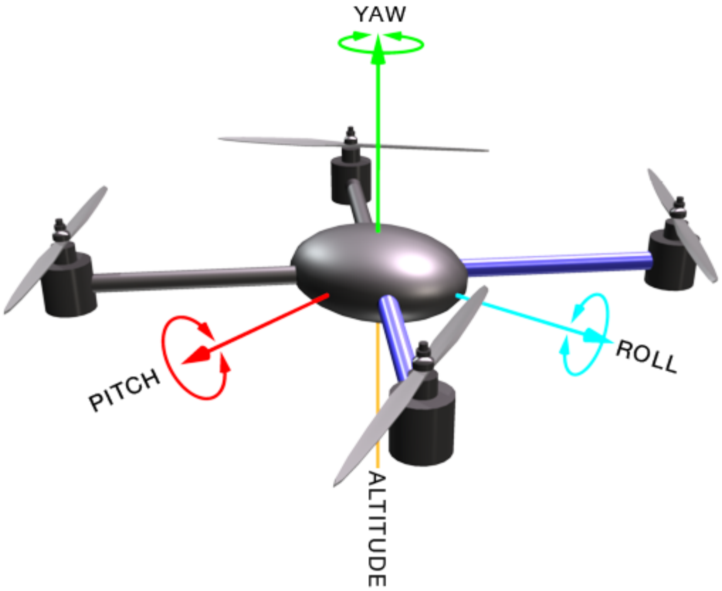


Figure 2.2: Roll, Pitch and Yaw angles [33]

## 2.2.2 Kinematics model

Before entering the physics of quadcopter motion, we have to formalize the kinematics upon the body and inertial frame. In the body frame, the linear velocities are determined by $V_B$ and the angular velocities by $\upsilon$[34].

$$V_B = \begin{bmatrix} V_{Bx} \\ V_{By} \\ V_{Bz} \end{bmatrix} \tag{2.2}$$

The angular velocities equal to $\dot{\eta} = \left(\dot{\phi}, \dot{\theta}, \dot{\Psi}\right)^T$ . However, note that the angular velocity vector $\upsilon \neq \dot{\theta}$ . The angular velocity $\upsilon = (p, q, r)^T$ is a vector pointing along the axis of rotation,

while is just the time derivative of yaw, pitch and roll.
The rotation matrix from the body frame to the inertial frame is,

$$R_{Rot} = \begin{bmatrix} C_\psi C_\theta & C_\psi S_\theta S_\phi - S_\psi C_\phi & C_\psi S_\theta C_\phi - S_\psi S_\phi \\ S_\psi C_\theta & S_\psi S_\theta S_\phi + C_\psi C_\phi & S_\psi S_\theta C_\phi + C_\psi S \\ -S_\theta & C_\theta S_\phi & C_\theta C_\phi \end{bmatrix} \tag{2.3}$$

In which $S_\alpha = sin(\alpha)$ and $C_\alpha = cos(\alpha)$. The rotation matrix $R$ is orthogonal thus $R^{-1} = R^T$ which is the rotation matrix from the inertial frame to the body frame.
The transformation matrix for angular velocities from the inertial frame to the body frame is $W_\eta$ , and from the body frame to the inertial frame is $W_\eta^{-1}$ ,

$$\dot{\eta} = W_\eta^{-1} \upsilon \tag{2.4}$$

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\Psi} \end{bmatrix} = \begin{bmatrix} 1 & S_\phi T_\theta & C_\phi T_\theta \\ 0 & C_\phi & -S_\phi \\ 0 & S_\phi / C_\theta & C_\phi / C_\theta \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{2.5}$$

$$\upsilon = W_n \dot{\eta} \tag{2.6}$$

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} 1 & 0 & -S_\phi \\ 0 & C_\phi & C_\phi S_\theta \\ 0 & -S_\phi & C_\theta C_\phi \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\Psi} \end{bmatrix} \tag{2.7}$$

In which $T_\alpha = tan(\alpha)$. The matrix $W_\eta$ is invertible if $\theta \neq (2k-1)\phi/2, (k \in Z)$.

### 2.2.3 Acceleration model

In order to calculate the acceleration of the quadcopter, the Newton-Euler formalization is used [31,34].

#### 2.2.3.1 Newton-Euler equations

The quadcopter is assumed to be rigid body and thus Newton-Euler equations can be used to describe its dynamics. In the body frame, the force required for the acceleration of mass and the centrifugal force are equal to the gravity and the total thrust of the rotors;

$$m\dot{V_B} + \upsilon \times (mV_B) = R^{\mathrm{T}} g + T_B \tag{2.8}$$

In the inertial frame, the centrifugal force is nullified. Thus, only the gravitational force and the magnitude and direction of the thrust are contributing in the acceleration of the quadcopter;

$$m\ddot{\varepsilon} = g + RT_B \tag{2.9}$$

$$\begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = -g \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} + \frac{T}{m} \begin{bmatrix} C_\Psi S_\theta C_\phi + S_\Psi S_\phi \\ S_\Psi S_\theta C_\phi - C_\Psi S_\phi \\ C_\theta C_\phi \end{bmatrix} \tag{2.10}$$

In the body frame, the angular acceleration of the inertia , the centripetal forces $\upsilon \times (I\upsilon)$ and the gyroscopic forces $\mathit{\Gamma}$ are equal to the external torque $\tau$. The quadcopter is assumed to have symmetric structure with the four arms aligned with the body $x$ and $y-axes$. Thus, the inertia matrix is diagonal matrix $I_n$.

$$I_n = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \tag{2.11}$$

$$I\dot{\upsilon} + \upsilon \times (I\upsilon) + \mathit{\Gamma} = \tau \tag{2.12}$$

$$\dot{\upsilon} = I_n^{-1} \left( - \begin{bmatrix} p \\ q \\ r \end{bmatrix} \times \begin{bmatrix} I_{xx}p \\ I_{yy}q \\ I_{zz}r \end{bmatrix} - I_r \begin{bmatrix} p \\ q \\ r \end{bmatrix} \times \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \omega_\Gamma + \tau \right) \tag{2.13}$$

$$\begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} (I_{yy} - I_{zz})qr/I_{xx} \\ (I_{zz} - I_{xx})pr/I_{yy} \\ (I_{xx} - I_{yy})pq/I_{zz} \end{bmatrix} - I_r \begin{bmatrix} q/I_{xx} \\ -p/I_{yy} \\ 0 \end{bmatrix} \omega_T + \begin{bmatrix} \tau_\phi/I_{xx} \\ \tau_\theta/I_{yy} \\ \tau_\Psi/I_{zz} \end{bmatrix} \tag{2.14}$$

Where , $\omega_T = \omega_1 - \omega_2 + \omega_3 - \omega_4$. The angular accelerations in the inertial frame are then attracted from the body frame accelerations with the transformation matrix $W_\eta^{-1}$ and its time derivative,

$$\ddot{\eta} = \frac{d}{dt}(W_\eta^{-1}\upsilon) = \frac{d}{dt}(W_\eta^{-1}\upsilon) + W_\eta^{-1}\dot{\upsilon} \tag{2.15}$$

$$\ddot{\eta} = \begin{bmatrix} 0 & \dot{\phi}C_\phi T_\theta + \dot{\theta}S_\phi/C_\theta^2 & -\dot{\phi}S_\phi C_\theta + \theta C_\phi^{\,\cdot}/C_\theta^2 \\ 0 & -\dot{\phi}S_\phi & -\dot{\phi}C_\phi \\ 0 & \dot{\phi}C_\phi/C_\theta + \dot{\phi}S_\phi T_\theta/C_\theta & -\dot{\phi}S_\phi/C_\theta + \dot{\theta}C_\phi T_\theta/C_\theta \end{bmatrix} \upsilon + W_\eta^{-1}\dot{\upsilon} \tag{2.16}$$

### 2.2.4 Physics

In order to properly model the dynamics of the quadcopter system, firstly we should understand its physical properties . At first stage , a quick description of the used motors on the quadcopter, as well as its power is introduced . We suppose that the four motors are identical, which means that we can analyze only one motor then apply it on the other three motors .The propellesr are mounted on opposite sides ,where two are clockwise and other two are counter clockwise on the Quad X configuration as shown in Figure 2.3[31,34].

#### 2.2.4.1 Motors model

In a brushless motor, the commutation of the windings is done not mechanically as before, but electronically by a compllicated system called "ESC or Electronic Speed Controller". This transforms the direct current into a three-phase current at a variable frequency and will power successively the motor coils to create the rotating field and therefore the rotation that interests us. The function of the produced torque is produced as follows.

$$\tau = k_t \left( I - I_0 \right) \tag{2.17}$$

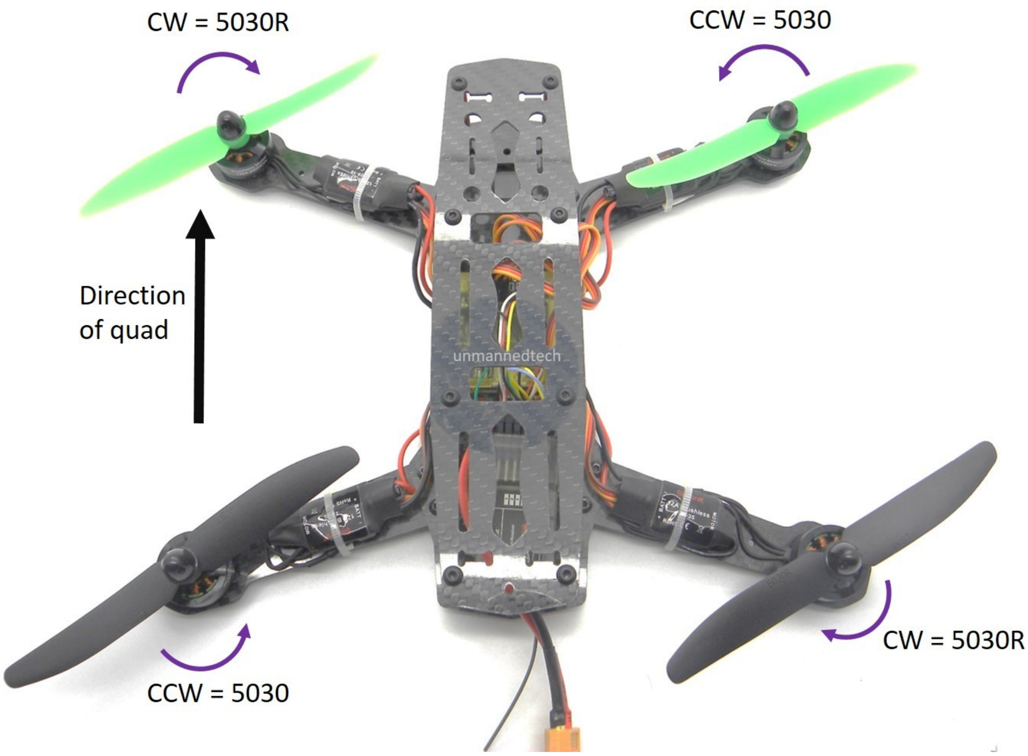


Figure 2.3: Propellers configuration on quadcopter [35].

Where:

- $\tau$: Motor torque ;
- $I$: Input current;

- $I_0$: No load current;
- $k_t$: Torque constant.

The voltage across the motor is given as follows ,

$$V = IR_m + k_v\omega \tag{2.18}$$

Where :

- $V$: Voltage drop across the motor ;
- $R_m$: Motor resistance ;
- $\omega$: Motors angular velocity ;
- $k_v$: Constant of RMF generated per rpm.

In order to calculate the consumed power, we use the following equation,

$$P = IV = \frac{(\tau + k_t I_0)(k_t I_0 R_m + \tau R_m + k_t k_v \omega)}{k_t^2} \tag{2.19}$$

To simplify the equation of power, we will assume that the motor resistance is negligible.

$$P \approx \frac{(\tau + k_t I_0) k_v \omega}{k_t} \tag{2.20}$$

To simplify this equation, we assume that $K_t I_0 \ll \tau$.

$$P \approx \frac{k_v}{k_t}\tau\omega \tag{2.21}$$

#### 2.2.4.2 Forces and Torques model

In the quadcopter, we have to modelize the forces and torques of both the motor and the quadcopter frame. Hence, we will give in what follows the full modeling equations.

#### a) Motors

The use of power in the quadcopter is to help it stay aloft, basing on the conservation of energy, then the power is generated like so ;

$$P = T\upsilon_h \tag{2.22}$$

When the vehicle is assumed low, $\nu_h$ is the air velocity when hovering, and the free stream velocity,$\upsilon_\infty$ is zero , the momentum equation for hover velocity as a function of thrust.

$$\upsilon_h = \sqrt{\frac{T}{2\rho A}} \tag{2.23}$$

Where :

- $\rho$: is the density of the surrounding air
- $A$: swept area by the rotor

Using the previous simplified equation for power, we obtain :

$$P = \frac{k_\upsilon}{k_t}\tau\omega = \frac{k_\upsilon k_\tau}{k_t}\mathrm{T}\omega = \frac{\mathrm{T}^{\frac{3}{2}}}{\sqrt{2\rho A}} \tag{2.24}$$

Generally $\tau = \vec{r} \times \vec{F}$. Hence, the torque is proportional to the thrust $T$, by some constant ratio $k_\tau$ determinated by the blade configuration and parameters. The thrust is given using the following equation;

$$T = \left(\frac{k_\nu k_t \sqrt{2\rho A}}{k_t}\omega\right)^2 = k\omega^2 \tag{2.25}$$

Where, $k$ is some appropriately dimensioned constant. Summing over all the motors, we find that the total thrust on the quadcopter (in the body frame) is given by ,

$$T_B = \sum_{i=1}^{4} T_i = k \begin{bmatrix} 0 \\ 0 \\ \sum \omega_i^2 \end{bmatrix} \tag{2.26}$$

In addition to the thrust force, we will model friction as a force proportional to the linear velocity in each direction. This is a highly simplified view of fluid friction, but will be sufficient for our modeling and simulation. Our global drag forces will be modeled by an additional force term .

$$F_D = \begin{bmatrix} -k_{d,x}\dot{x} \\ -k_{d,y}\dot{y} \\ -k_{d,z}\dot{z} \end{bmatrix} \tag{2.27}$$

If additional precision is desired, the constant $k_d$ can be separated into three separate friction constants, one for each direction of motion. If we were to do this, we would want to model friction in the body frame rather than the inertial frame.

## a.1) Torques model

Each rotor contributes some torque about the body $z$ axis. This torque is the torque required to keep the propeller spinning and providing thrust; it creates the instantaneous angular acceleration and overcomes the frictional drag forces. The drag equation from fluid dynamics gives us the frictional force as folows;

$$F_D = \frac{1}{2}\rho C_D A v^2 \tag{2.28}$$

Where, $\rho$ is the surrounding fluid density, A is the reference area (propeller cross-section, not area swept out by the propeller), and $C_D$ is a dimensionless constant. This, while only accurate in some in some cases, is good enough for our purposes. This implies that the torque due to drag is given by

$$\tau_D = \frac{1}{2}R\rho C_D A v^2 = \frac{1}{2}R\rho C_D A(\omega R)^2 = b\omega^2 \tag{2.29}$$

Where, $\omega$ is the angular velocity of the propeller,$R$ is the radius of the propeller, and b is some appropriately dimensioned constant. Note that we've assumed that all the force is applied at the tip of the propeller, which is certainly inaccurate; however, the only result that matters for our purposes is that the drag torque is proportional to the square of the angular velocity. We can then write the complete torque about the $z$ axis for the $i^{th}$ motor:

$$\tau_z = b\omega^2 + I_M\dot{\omega} \tag{2.30}$$

Where,$I_M$ is the moment of inertia about the motor $z$ axis, is the angular acceleration of the propeller, and $b$ is our drag coefficient. Note that in steady state flight (i.e. not take off or landing), , since most of the time the propellers will be maintaining a constant (or almost constant) thrust and won't be accelerating. Thus, we ignore this term, simplifying the entire expression to,

$$\tau_z = (-1)^{i+1} b\omega_i^2 \tag{2.31}$$

Where the$(-1)^{i+1}$ term is positive for the $i^{th}$ propeller if the propeller is spinning clockwise and negative if it is spinning counterclockwise. The total torque about the $z$ axis is given by the sum of all the torques from each propeller:

$$\tau_\psi = b\left(\omega_1^2 - \omega_2^2 + \omega_3^2 - \omega_4^2\right) \tag{2.32}$$

The roll and pitch torques are derived from standard mechanics. We can arbitrarily choose the $i = 1$ and $i = 3$ motors to be on the roll axis,

$$\tau_\phi = \sum r \times T = L_D \left(k\omega_1^2 - k\omega_3^2\right) = Lk \left(\omega_1^2 - \omega_3^2\right) \tag{2.33}$$

Correspondingly, the pitch torque is given by a similar expression,

$$\tau_\theta = L_D k \left(\omega_2^2 - \omega_4^2\right) \tag{2.34}$$

Where, $L_D$ is the distance from the center of the quadcopter to any of the propellers. All together, we find that the torques in the body frame are;

$$\tau_B = \begin{bmatrix} L_D k \left(\omega_1^2 - \omega_3^2\right) \\ L_D k \left(\omega_2^2 - \omega_4^2\right) \\ b \left(\omega_1^2 - \omega_2^2 + \omega_3^2 - \omega_4^2\right) \end{bmatrix} \tag{2.35}$$

The model we've derived so far is highly simplified. We ignore a multitude of advanced effects that contribute to the highly nonlinear dynamics of a quadcopter. We ignore rotational drag forces (our rotational velocities are relatively low), blade flapping (deformation of propeller blades due to high velocities and flexible materials), surrounding fluid velocities (wind), etc. With that said, we now have all the parts necessary to write out the dynamics of our quadcopter.

## b) Quadcopter model

To determine the forces and torques of the hall quadcopter, we will use the Euler-Lagrange equations [31,34].

### Euler-Lagrange equations

The Lagrangian $\mathcal{L}$ is the sum of the translational $E_{trans}$ and rotational $E_{rot}$ energies minus potential energy $E_{pot}$

$$\mathcal{L}(q, \dot{q}) = E_{trans} + E_{rot} - E_{pot} \tag{2.36}$$

$$\mathcal{L}(q, \dot{q}) = (m/2)\dot{\varepsilon}^T \dot{\varepsilon} + (1/2)\, \upsilon^T I \upsilon - mgz \tag{2.37}$$

As shown in [10] the Euler-Lagrange equations with external forces and torques are;

$$\begin{bmatrix} f \\ \tau \end{bmatrix} = \frac{d}{dt}\left(\frac{\partial \mathcal{L}}{\partial \dot{q}}\right) - \frac{\partial \mathcal{L}}{\partial q} \tag{2.38}$$

The linear and angular components do not depend on each other thus they can be studied separately. The linear external force is the total thrust of the rotors. The linear Euler-Lagrange equations are

$$f = RT_B = m\ddot{\varepsilon} + mg\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{2.39}$$

The Jacobian matrix $J(\eta)$ from $\nu$ to $\dot{\eta}$ is

$$J\ (\eta)\ = J = W_\eta^T I_n W_n \tag{2.40}$$

$$= \begin{bmatrix} I_{xx} & 0 & -I_{xx}S_\theta \\ 0 & I_{yy}C_\phi^2 + I_{zz}S_\phi^2 & (I_{yy} - I_{zz})C_\phi S_\phi C_\theta \\ -I_{xx}S_\theta & (I_{yy} - I_{zz})C_\phi S_\phi C_\theta & I_{xx}S_\theta^2 + I_{zz}S_\phi^2 C_\theta^2 + I_{zz}C_\phi^2 C_\theta^2 \end{bmatrix} \tag{2.41}$$

Thus, the rotational energy $E_{rot}$ can be expressed in the inertial frame as

$$E_{rot} = (1/2)\,\upsilon^T I_n \upsilon = (1/2)\,\ddot{\eta}^T J \ddot{\eta} \tag{2.42}$$

The external angular force is the torques of the rotors. The angular Euler-Lagrange equations are

$$\tau = \tau_B = J\ddot{\eta} + \frac{d}{dt}(J)\,\dot{\eta} - \frac{1}{2}\frac{\partial}{\partial\eta}\left(\dot{\eta}^T J \dot{\eta}\right) = J\ddot{\eta} + C(\eta, \dot{\eta})\,\dot{\eta} \tag{2.43}$$

In which the matrix $C(\eta, \dot{\eta})$ is the Coriolis term, containing the gyroscopic and centripetal terms. The matrix $C(\eta, \dot{\eta})$ has the form, as shown in [35],

$$C(\eta, \dot{\eta}) = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix} \tag{2.44}$$

$C_{11} = 0$
$C_{12} = (I_{yy} - I_{zz})(\dot{\theta}C_\phi S_\phi + \dot{\psi}S_\phi^2 C_\theta) + (I_{zz} - I_{yy})\dot{\psi}C_\phi^2 C_\theta - I_{xx}\dot{\psi}C_\theta$
$C_{13} = (I_{zz} - I_{yy})\dot{\psi}C_\phi S_\phi C_\theta^2$
$C_{21} = (I_{zz} - I_{yy})(\dot{\theta}C_\phi S_\phi + \dot{\psi}S_\phi C_\theta) + (I_{yy} - I_{zz})\dot{\psi}C_\phi^2 C_\theta + I_{xx}\dot{\psi}C_\theta$
$C_{22} = (I_{zz} - I_{yy})\dot{\phi}C_\phi S_\phi$
$C_{23} = -I_{xx}\dot{\psi}S_\theta C_\theta + I_{yy}\dot{\psi}S_\phi^2 S_\theta C_\theta + I_{zz}\dot{\psi}C_\phi^2 S_\theta C_\theta$
$C_{31} = (I_{yy} - I_{zz})\dot{\psi}C_\phi S_\phi C_\theta^2 - I_{xx}\dot{\theta}C_\theta$
$C_{32} = (I_{zz} - I_{yy})(\dot{\theta}C_\phi S_\phi S_\theta + \dot{\phi}S_\phi^2 C_\theta) + (I_{yy} - I_{zz})\dot{\phi}C_\phi^2 C_\phi + I_{xx}\dot{\psi}S_\theta C_\theta - I_{yy}\dot{\psi}S_\phi^2 S_\theta C_\theta - I_{zz}\dot{\psi}C_\phi^2 S_\theta C_\theta$
$C_{33} = (I_{yy} - I_{zz})\dot{\phi}C_\phi S_\phi C_\theta^2 - I_{yy}\dot{\theta}S_\phi^2 S_\theta C_\theta - I_{zz}\dot{\theta}C_\phi^2 S_\theta C_\theta + I_{xx}\dot{\theta}S_\theta C_\theta$\tau={{k}_{t}}\left(I-{{I}_{0}}\right)

Equations (2.43) leads to the differential equations for the angular accelerations which are equivalent with Equations (2.12-2.16)

$$\ddot{\eta} = J^{-1}(\tau_B - C(\eta, \dot{\eta})\dot{\eta}) \tag{2.45}$$

#### 2.2.4.3 Aerodynamical effects model

The preceding model is a simplification of complex dynamic interactions. To enforce more realistically behavior of the quadcopter, drag force generated by the air resistance is included ,

$$\begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = -g \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} + \frac{T}{m} \begin{bmatrix} C_\psi S_\theta C_\phi + S_\psi S_\theta \\ S_\psi S_\theta C_\phi - C_\psi S_\phi \\ C_\theta C_\phi \end{bmatrix} - \frac{1}{m} \begin{bmatrix} A_x & 0 & 0 \\ 0 & A_y & 0 \\ 0 & 0 & A_z \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} \tag{2.46}$$

In which $Ax$, $Ay$ and $Az$ are the drag force coefficients for velocities in the corresponding directions of the inertial frame. Where:
$K_{d,x} = \frac{A_x}{m}$ , $K_{d,y} = \frac{A_y}{m}$ $K_{d,z} = \frac{A_y}{m}$

Several other aerodynamical effects could be included in the model.The influence of aerodynamical effects are complicated and the effects are diffcult to model. Also some of the effects have significant effect only in high velocities. Thus, these effects are excluded from the model and the presented simple model is used [30].

In our dissertation , we aim to stabilize the quadcopter . Hence , a control method should be used to control the rotation of brushless motors and then maintain the stability of the quadcopter . In what follows , we will give a brief description of the brushless motors , which are the main component to control in quadcopters.

## 2.3 Brushless motors

To control the drone and to make it moves in all directions, we need an opposing force to the strength of its gravity and more than it is intensity capable of doing all of the instructions provided via the remote control tool. For this we use the electrical motors attached to the propellers and since the motors are many types, the one we use is called brushless motors.

### 2.3.1 Definition

Brushless motor mean a motor without brushes, called too synchronous self-piloting machine with permanent magnets, is an electric machine of the category of synchronous machines, whose rotor consists of one or more permanent magnets and provided with an original rotor position sensor called Hall effect sensor, synchro-resolver or a rotary encoder (for example incremental encoder), or any other system allowing the machine to self-control. DC motors with brushes cause friction and limit the life of the engine by their wear.

To avoid all these problems we use brushless motors because this type of electric motor eliminates all the disadvantages of the conventional direct current motor : switching problems at the level of the collector, shrinking, inertia, cooling (the joule losses being located on the stator they are easier to evacuate), much higher mass power, geometry, lifetime ; in particular the protection index (IP) can be increased compared to DC machines due to the absence of brushes.[36]

## 2.3.2 Types of brushless motors

### 2.3.2.1 Brushless outrunner motors

Brushless motors whose rotor is around the stator are called "outrunner". This configuration is interesting in terms of engine torque, because the magnets are arranged over a large diameter, which creates a very interesting lever arm. In addition, this arrangement makes it easy to place several sets of magnets (up to 32 poles on certain outrunner brushless motors) and coils.

The coils are always wired in groups of 3, and the magnets are either glued in groups of 2, or consist of a magnetic part comprising several poles. Like a stepper motor, outrunners brushless motors with more than 3 coils and 2 poles only make a fraction of a turn when the field has rotated 180°. Their frequency of rotation is therefore lower but the torque very high.
These outrunner brushless motors are often used in applications that require a high torque, because they can be connected to the load without requiring a reduction device. Their Kv coefficient is relatively low compared to other types of brushless motors. [37]

Figure 2.4: Outrunner brushless motor [38]

**Advantage of external motor** First, an advantage of the outer rotor motor over the inner rotor motor is that the area of the air gap is considerably greater. In other words, the area crossed by the electromagnetic field lines between the rotor and the stator is much larger. A higher electromechanical force is thus generated.

In addition, the torque arm of an external rotor motor is longer because the force is exerted at a greater distance from the center of rotation. A larger air gap and a longer torque arm therefore result in greater torque. As a result, motors with an external rotor make it possible to obtain much higher torque values than those obtained with motors with an internal rotor of the same construction volume. [37]

#### 2.3.2.2 Inrunner brushless motors

Unlike the previous type, brushless inrunners have the rotor inside the stator. They usually only have one pair of poles on the rotor, and 3 coils on the stator. The inertia of the rotor is much lower than for an outrunner motor, and the speeds reached by this type of motor are much higher (Kv up to 7700 rpm / V).

The electronic switching management is however more simple because the rotor rotates at the same frequency as the magnetic field. The torque of brushless inrunners motors is lower than for an outrunner because the magnets are on a smaller diameter for equal motor size. This type of brushless motor is widely used in the industry because it is very similar to a DC brushed motor and collector. [37]

Figure 2.5: Inrunner brushless motor [39]

#### 2.3.2.3 Brushless disc motors

The rotor and the stator can also consist of two discs facing each other, with the spokes and the coils distributed along the spokes of these two discs. This type of brushless motor is little used because the action of the coils on the magnets creates a large axial force which requires substantial thrust bearings, without offering significant differences in performance compared to a brushless outrunner motor. [37]

Figure 2.6: Brusless disk motor [40]

### 2.3.3 Components of the brushless motor

Structurally, this motor has the same structure as a DC motor. However, the differences between them lie in the absence of the brushes in this type of motors in addition to that the rotor is external in the brushless outrunner motor and consists of a permanent magnet; the opposite of the stator which is internal and consists of a winding traversed by an electric current. [41]

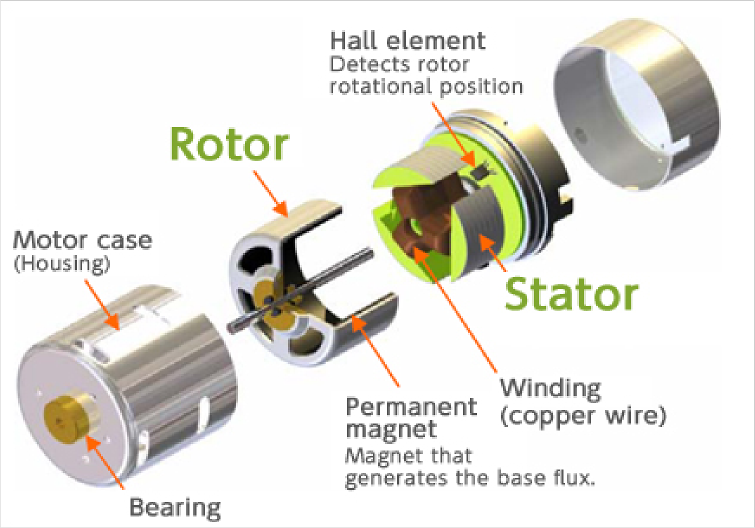


Figure 2.7: Brusless motors components and structure [42]

#### 2.3.3.1 Brusless outrunner motor structure [41]

- The stator, a material with high mgnetic permeability, often formed of 9 or 12 teeth carrying the coils.
- The magnets are glued on the external bells to represent a north-south alternation forms the rotor. 12 magnets for 9 teeth and 14 for 12 teeth.
- Copper wire windings can be on each tooth or on every two tooths.
- The copper wires on the teeth are connected in series to form only 3 coils.

**For example in the case of 9 windings for 9 teeth [41]**

- windings 1,4,7 form the coil L1
- Windings 2,5,8 form the coil L2
- Windings 3,6,9 form the coil L3 [41]

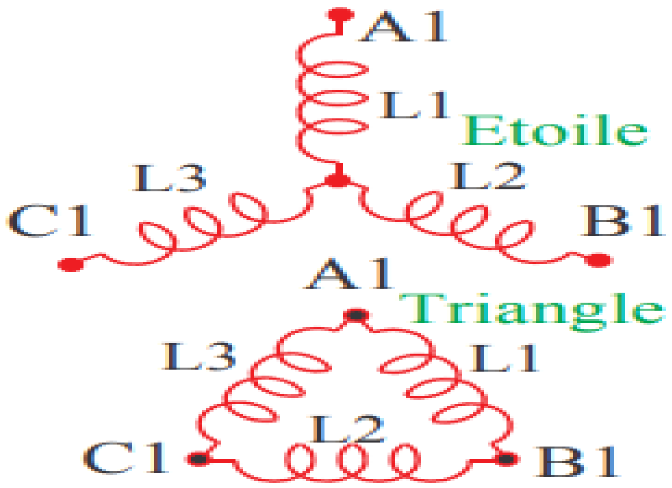


Figure 2.8: Star and triangle coupling [41]

- The connection of the coils will be in star or in triangle.
- In the star arrangement the coils in series have a greater impedence.
- In the triangle connexion the parallel impedances have a smaller impedance. [41]

**we obtain the same power with**

1. In the star connexion, with more voltage for less current.
2. In the triangle connexion, with less voltage for less current. [41]

## 2.3.4 Motor operating mode

### 2.3.4.1 Step-by-step mode

A voltage is applied between the poles of the coils and the 3 rd in the air, wait until the rotor comes to rest (equilibrium position). We switch the voltage from the terminal to the terminal which was in the air, change the polarity of a stator tooth and wait until the rotor takes its new position and as this the motor will turn step by step. [41]

### 2.3.4.2 Rotor position detection mode

Measurement of the voltage induced in the open circuit coil. By launching the motor in step mode the microcontroller leaves the terminals of the coils in the air and notes the position where the induced voltage in the coil passes through zero (maximum flux) it is the position where the tooth and the magnet are closer, at this moment the microcontroller make a new switching. [41]

### 2.3.5 Motor power balance [41]

**Power supplied by the battery**

$$Pbatt = V.I \tag{2.47}$$

**Power lost by Joule effect**

$$Pj = (Rc + Rb)I^2 \tag{2.48}$$

**power lost by friction and the magnetic circuit**

$$Pf = VmI0, Vm = V - (Rc + Rb)I, Pf = [V - (Rc + Rb)I)]I0. \tag{2.49}$$

**Useful engine power transmitted to the propeller**

$$Ph = Vm(I - I0) \tag{2.50}$$

$$Ph = [V - (Rc + Rb)I](I - I0) \tag{2.51}$$

**yield**

$$\rho = Ph/Pbatt \tag{2.52}$$

$$I_{opt} = (I_0 \times I_{cc})^{1/2} \tag{2.53}$$

$$I_{cc} = V/(R_c + R_b) \tag{2.54}$$

**Maximum yield**

$$\rho_{max} = (\sqrt{I_{cc}} - \sqrt{I_0})^2 / I_{cc} \tag{2.55}$$

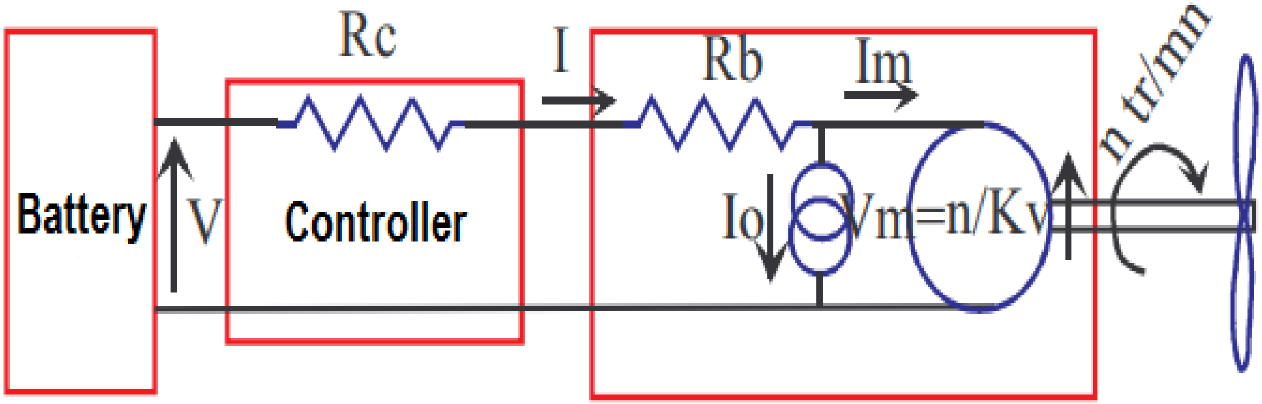


Figure 2.9: Energy transformation schema [41]

## 2.3.6 Electromechanical principle of the motor and its control

### 2.3.6.1 Physical interpretation

The source of the dynamic force that spins the motor is based on the same principle as the magnet, so that the approximation of two similar poles results a repulsive force and two different poles are attracted.

Also, the magnetization, which is a transfer of charges or free electrons searching for stability, is present either in the magnetic bar or also when we pass an electrical current in an electrical conductor that produces a magnetic field similar to the first and a force known as (The Laplace force) what expresses the base of the right hand.

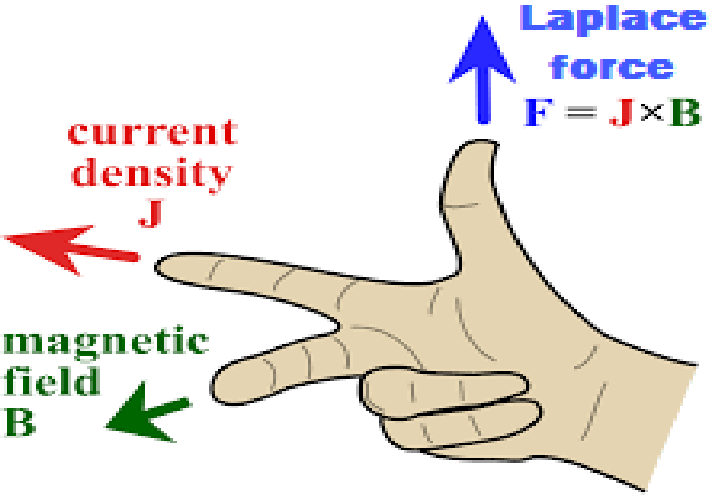


Figure 2.10: Right hand rule [42]

In the motor, when a pole from the stator meet a pole from the rotor having the same charges (negative or positive) so repulsion occurs between them, and since the stator is fixed, the rotor is the one that moves and rotates towards the magnetic field to reach the other pole in search of discharging the charges and stability.
So we ship that coil in the same way, repulsion occurs, and this is how it happens with each pole, so the rotating part remains in a continuous and increasing rotational movement until it reaches the maximum speed.

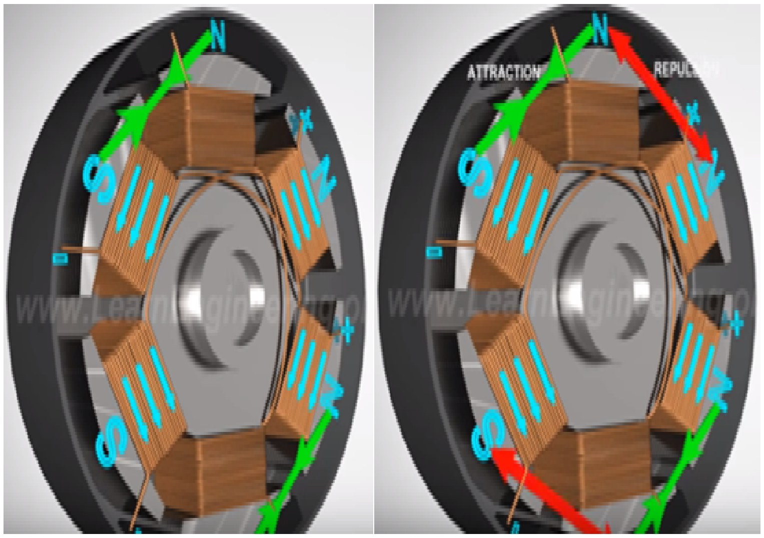


Figure 2.11: attraction and expulsion forces [43]

Its speed is controlled by changing the charging current or changing the frequency, and since the frequency is constant (50Hz), its speed is controlled only by the induction current. As for the direction of rotation, it depends on the direction of the current (if we want to reverse the direction of the motor rotation, we reverse the poles of the electrical induction).

### 2.3.7 The characteristics of drone motors

There are various types of motors characterized by the size, the speed of rotation (KV) and the electric voltage that they can support. The first two parameters are engraved on the motor. [44]

#### 2.3.7.1 Motor size

- The first four digits indicated on the motor correspond to the diameter of the stator (2 digits) and the height of the stator (2 digits), expressed in millimeters. Thus, a 2206 motor has a diameter of 22 mm and a height of 6 mm.
- The size of the motor, in particular the diameter, must be compatible with the chassis. The size of the chassis affects the spacing of the motor fixing screws. Thus, it is necessary to choose suitable motors so that the configuration remains compatible.
- The size of the engine influences its weight, which has consequences on the drone's handling in flight‘.

#### 2.3.7.2 Rotation speed

- The following four digits indicate the number of revolutions that the engine can make in 1 minute and for 1 volt when empty. The KV characterizes the property of the engine to transform the power it receives into speed, or torque. This value is expressed in Kilovolt.
- Thus, an engine with a low KV will be more torquey and can be combined with a propeller having a greater inclination of the blades.
- A motor with a high KV will not tolerate too much inclination of the blades. This could cause overheating and excessive consumption .

#### 2.3.7.3 Electrical voltage

- The choice of KV is linked to the choice of battery. The motor supports a certain voltage or electric voltage expressed in number of cells (S). Generally, the characteristics of the engine presented by the supplier or the seller indicate a range of the number of cells it takes for its proper functioning.
- Ultimately, choosing an engine can be complex because all the characteristics of the engines, propellers, ECS and battery must be harmonized and adapted to the type of flight desired by the pilot.

In an experimental point of view , the coils are fed sequentially. This creates a magnetic field rotating at the same frequency as the supply voltages (50 Hertz). The permanent magnet of the rotor constantly seeks to orient itself in the direction of the field. For the brushless motor to rotate, the supply voltages must be continuously adjusted so that the field remains ahead of the rotor position, and thus create motor torque.

An electronic control system must ensure the switching of the current in the stator windings. This device can be either integrated into the motor for small powers, or external in the form of a power converter (inverter). The role of the sensor plus electronic control assembly is to ensure self-control of the motor, that is to say the orthogonality of the rotor magnetic flux with respect to the stator flux.

### 2.3.8 Self-synchronism

Synchronism in the machines means that the speed of the rotating field is equal to the speed of rotation (sliding = 0). Auto-synchronism means that the motor has the possibility of synchronizing the two speeds automatically, so a position sensor (encoder or resolver) is added which detects the exact position of the rotor and allows the frequency converter to maintain an angle of 90 ° (sin  = 1) between the stator rotating field Hs and the rotor field Hr in order to always have attractive force and repulsive force in the same direction that results a maximum torque.

$$Cem = K.I.Sin\varPhi \rightarrow \varPhi = \varPi/2 \rightarrow Sin\varPhi = 1. \tag{2.56}$$

### 2.3.9 The choice of motor and propellers [45]

The first step, therefore, consists in choosing the type of flight, which can be classified into three categories:

- Nervous (athletic, acrobatic, speed);
- Versatile (in between);
- Stable (ballad, shooting)

#### 2.3.9.1 Drone propellers

The technical characteristics of the propellers have two values: The length of the blades and the geometric pitch, both expressed in inches.

Reminder of what is the pitch of a propeller. The pitch is the distance that the propeller travels in making a full turn without "sliding". In other words, by keeping a linear trajectory. The pitch of a propeller varies according to the number of its blades, the weight of the machine and the atmospheric pressure. This is why it is important to distinguish between the geometric step, which is the theoretical and inflexible value, and the effective step, which is the real step.

To summarize on the propellers of a drone

- **Large Propeller** = a lot of lift → stable flight but needs power to make 1 full turn → large engine.
- **Small Propeller** = little lift → less stable flight and needs less power to make 1 full turn → weak engine.

The size of the propeller does this depending on the lift (ie the mass to be flown) that we need. For a quadricopter for example, the size varies between 8 ″ and 13 ″ to that you have to take into account the size of the chassis: For a 30cm chassis you can climb to 9 ″ max, on 450cm you can climb from 12 ″ max.

- Small step = greater traction at low speed, but maximum speed limited.
- Big step = smallest traction at low speed, but high maximum speed.

The size of the geometric step depends on the speed you want to reach.

For a quadricopter, the average is 4.5 ″. It is however possible to descend to 3.5 (for slow flight) or to climb to 6 (for fast flight) .

**Motors and battery:** Links that will allow you to determine the right flight time.

The choice of motors is based on their performance, ie the number of revolutions that the motor can make in 1 minute and for 1 volt. This value is expressed in Kilo Volt denoted KV. The higher the KV of a large engine, the better its efficiency and therefore more energy efficient. This is why it is closely linked to the choice of battery

.

Below is a table that summarizes the previous paragraphs. These values are theoretical, but the objective of this table is to allow anyone wishing to manufacture a drone to have better visibility in the choice of engines and propeller.

Table 2.1: Propeller choice types

| | Nervous flight | Versatile flight | Stable flight |
|---|---|---|---|
| Propeller (length in inch) | 8 | 8-10 | 10-11 |
| geometric pitch (in inches) | 5 | 4.5-5 | 4-4.5 |
| rpm | 12 000 | 10 000 | 8 000 |
| KV | 1100-1400 | 900-1100 | 700-900 |

### 2.3.10 Brushless motors areas of use [41]

- **The main applications of outrunners brushless motors**

1. Fans;
2. Hard drive motors;
3. CD-ROM;
4. Electric bicycle motors (integrated in hub);
5. Radio-controlled boats or planes.

- **Brushless inrunner motors**

Are widely used in industry because they come close a lot of to a DC brushed motor and collector .

- **Brushless disc motors**

Are rarely used because the action of the coils on the magnets creates a significant axial force which requires substantial thrust ball bearings, without offering any notable differences in performance compared to a brushless motor outrunner .

### 2.3.11 Disadvantages of brushless motor [41]

- Absence of brushes obliges to interpose a controller between the battery and the motor. A complexe component, generates a three-phase voltage synchronous with the rotor. device that has become reliable but more expensive than a conventional variable speed drive.
- When converting electricity into mechanical power, brushless motors are more efficient than brushed motors. This improvement is largely due to the frequency at which the electricity is switched determined by the position sensor feedback. Additional gains are due to the absence of brushes, which reduces mechanical energy loss due to friction.

## 2.4 Quadcopter control methods

Several methods can be found in the literature , where the main objective is to control the speed of the four brushless motors of the quadcopter. The controlling of these motors can guarantee the stability against the perturbation occurring during the quadcopters fly . In what follow , we will give a brief overview of some most used control methods for quadcopters stability.

### 2.4.1 Proportional Integral Derivative (PID)

The PID controller has been applied to a broad range of controller applications. It is indeed the most applied controller in industry . The classical PID linear controller has the advantage that parameter gains are easy to adjust, is simple to design and has good robustness [47].

### 2.4.2 Adaptive controller

The adaptive control is an advance control technique which provides a systematic approach for automatic adjustment of controllers in real time, in order to achieve or to maintain a desired level of control system performance, when the parameters of the plant dynamic model are unknown and/or change in time[48].

### 2.4.3 Model reference adaptive control or MRAC

Is a direct adaptive strategy which consists of some adjustable controller parameters and an adjusting mechanism to adjust them. The goal of the MRAC approach is adjusting the controller parameters so that the output of the plant tracks the output of the reference model having the same reference input [48].

### 2.4.4 Sliding mode control (SMC)

The basic idea of sliding regime control is first to draw the states of the system to a suitably selected region, and then to design a control law that will always maintain the system in that region.

As a summary , the following gives a comparison between the most used control methods for quadcopter stability [49].

Table 2.2: Comparison of quadrotor control algorithms.

| Control Algorithme | Charractristics | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Robuste | Adaptative | Optimal | Intelligent | Trachking ability | fast convergence/rsponse | Precision | Simplicity | Disturbance rejection | Unmodeled parametre handling | Manual tuning | (Signal) noise | Chettering/energy loss |
| PID | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 2 | 0 | 0 | 2 | 2 | 0 |
| Intelligent | 1 | 0 | 0 | 2 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |
| LQR | 0 | 2 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 |
| LQG | 0 | 2 | 2 | 0 | 1 | 1 | 0 | 0 | 2 | 0 | 1 | 0 | 0 |
| $L_1$ | 0 | 2 | 2 | 0 | 1 | 2 | 2 | 0 | 1 | 0 | 0 | 0 | 0 |
| $H_1$ | 2 | 1 | 2 | 0 | 2 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 |
| SMC | 1 | 2 | 1 | 0 | 2 | 2 | 2 | 1 | 2 | 1 | 0 | 0 | 2 |
| FBL | 1 | 1 | 0 | 0 | 2 | 2 | 2 | 1 | 1 | 1 | 0 | 1 | 0 |
| Backstepping | 0 | 2 | 0 | 0 | 2 | 0 | 1 | 0 | 2 | 1 | 0 | 0 | 0 |
| Fuzzy Logic | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 |
| Neural networks | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 |
| Genetic | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 0 | 1 | 2 | 0 | 0 | 0 |

Legend: 0—low to none; 1—average; 2—high. Also, 1 through 5 (Linear); 6 through 12 (Nonlinear).

## 2.5 Conclusion

Stability is the main problem facing any quadcopter industry. In order to perform this , a full and detailed overview of mathematical modelling of quadcopters is given in this chapter. It is clearly shown the importance of the mathematical modelling for further control schemes in order to stabilize the movement of the chosen quadcopter.

The control of the four motors speed of the quadcopter can perform several movement in order to move the UAV to any place in the space. Several methods are found in literature to perform this task. The next chapter , will focus on applying PID control on the mini-drones in order to achieve their stability.

# Chapter 3

# Simulation Results

## 3.1 Introduction

Controlling the quadcopter is the main part in order to make fly smoothly . these control methods are mainly used to stabilize the Altitude, Roll, Pitch and Yaw angles. The objective is to compare their performance in the quadcopter stability point of view. In this chapter , PID control is applied in order to stabilize the mini drone.

Several tuning parameters has been tested in order to know the range of the PID gains to be implemented in the real cases. A Matlab/ Simulink model was developed taking into consideration a real quadcopter components parameter.

## 3.2 Proportional Integral Derivative (PID)

It is a system control technique. Practically, it is an instrument made of several electrical components with a programming algorithm which is responsible for maintaining the stable state of our system and its performances (fast, stable, rigid). A sensor must measure the instantaneous values of the system and transfer them to a comparator which gives the difference between this value and the desired set point, this difference is called the error which is the important parameter in regulation.

After we take the error, we integrate it into the PID corrector and the last will calculate the appropriate gains to restore the normal state of the system after the external disturbance and must impose this correction on the process. All this operations must takes place in the real time.

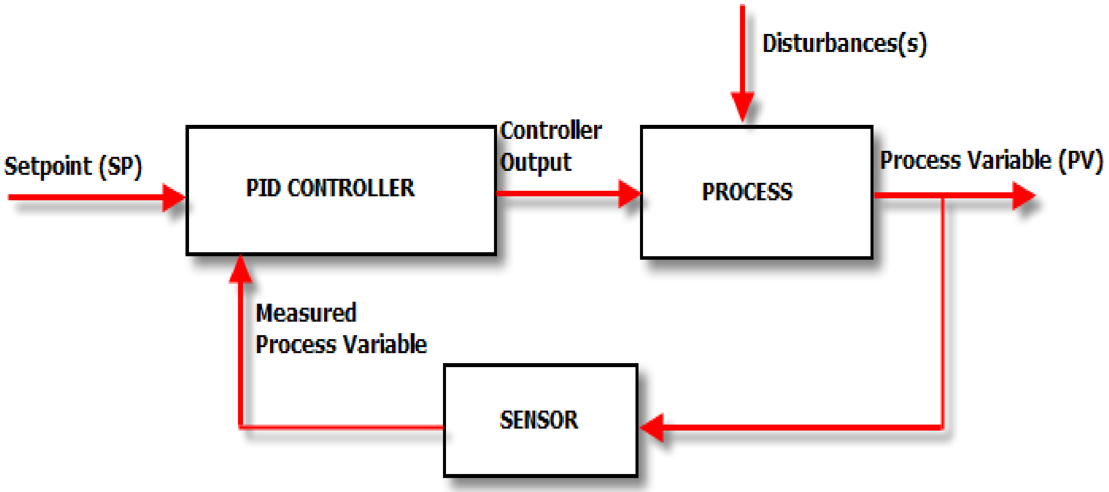


Figure 3.1: Closed loop with PID regulator [50]

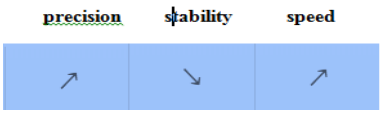
### 3.2.1 Proportional Action

Is the most intuitive of the three. It is a question of applying a coefficient Kp to the error.

$$Kp \times e(t) \tag{3.1}$$

This is like what we do on driving : when the car starts to deviate from its path, on gives a steering wheel kick in the opposite direction. The error here is the difference between the desired trajectory and that estimated by our eyes and the correction proportional to the error.

More we increase the gain, the system reacts rapidly , but it then gains instability and loses precision. [51]



| precision | stability | speed |
|---|---|---|
| ↗ | ↘ | ↗ |

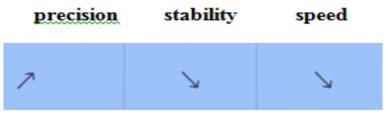
Figure 3.2: System performance with a P action [51]

### 3.2.2 Integral action

The integral action consists in summing the measured errors over time and applying a coefficient Ki to the set:

$$Ki \int_0^t e(t)dt \tag{3.2}$$

This component reduces the static error and therefore improves the accuracy of the system. On the other hand, it increases instability and decreases speed [51].



| precision | stability | speed |
|---|---|---|
| ↗ | ↘ | ↘ |

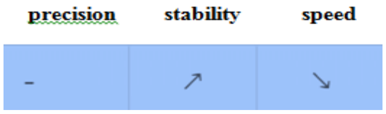
Figure 3.3: System performance with a I action [51]

### 3.2.3 Derivative Action

The derived action consists in calculating the difference between the current error and the error at t-1 and applying a coefficient Kd to the result [51].

$$Kd(de(t))/dt \tag{3.3}$$

This component increases the stability of the system but at the expense of speed.



| precision | stability | speed |
|---|---|---|
| - | ↗ | ↘ |

Figure 3.4: System performance with a D action [51]

Here we show the names of some important points in the result of controlling the system

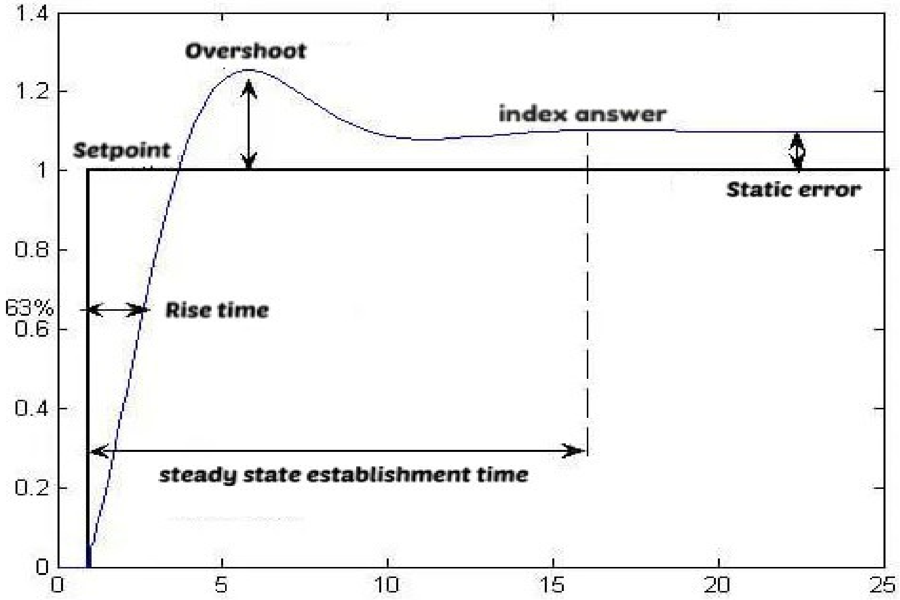


Figure 3.5: Key points of 2nd degree freedom system [51]

PID controller for quadcopters These controller algorithms are translated into software code lines. To have any kind of control over the quadcopter, we need to be able to measure the Quadcopter sensor output (for example the pitch angle), so we can estimate the error (how far we are from the desired pitch angle, e.g. horizontal, 0 degree).

We can then apply the 3 control algorithms to the error, to get the next outputs for the motors aiming to correct the error.

### 3.2.4 Effect of each parameter

The variation of each of these parameters alters the effectiveness of the stabilization. Gener ally there are 3 PID loops with their own PID coefficient, one per axis, so you will have to set P, I and D values for each axis (pitch , roll  and yaw ) to a quadcopter, these parameters can cause this behavior.

• Proportional Gain coefficient: this coefficient determines which is more important, human control or the values measured by the gyroscopes. The higher the coefficient, the higher the Quadcopter seems more sensitive and reactive to angular change. If it is too low, the Quadcopter will appear sluggish and will be harder to keep steady. Sometimes, we could find the Quadcopter starts to oscillate with a high frequency when P gain is too high.

• Integral Gain coefficient: this coefficient can increase the precision of the angular position. For example, when the Quadcopter is disturbed and its angle changes from, in theory it remembers how much the angle has changed and will return. In practice if we make the Quadcopter go forward and the force it to stop, the Quadcopter will continue for some time to counteract the action. Without this term, the opposition does not last as long.

This term is especially useful with irregular wind, and ground effect (turbulence from motors). However, when the I value get too high , the Quadcopter might begin to have slow reaction and a decrease effect of the proportional gain as consequence, it will also start to oscillate like having high P gain, but with a lower frequency.

- Derivative Gain coefficient: this coefficient allows the Quadcopter to reach more quickly the desired attitude. It called also the accelerator parameter because it implies the user input. It also decreases control action fast when the error is decreasing fast. In particle it will increase the reaction speed and in certain cases an increase the effect of the P gains.

## 3.3 Simulation results

In this part, a modelisation of mini quadcopter is achieved , a solid work software was used to generate 3D le to be implemented in Simulink. The simulation block diagram is shown in Figure

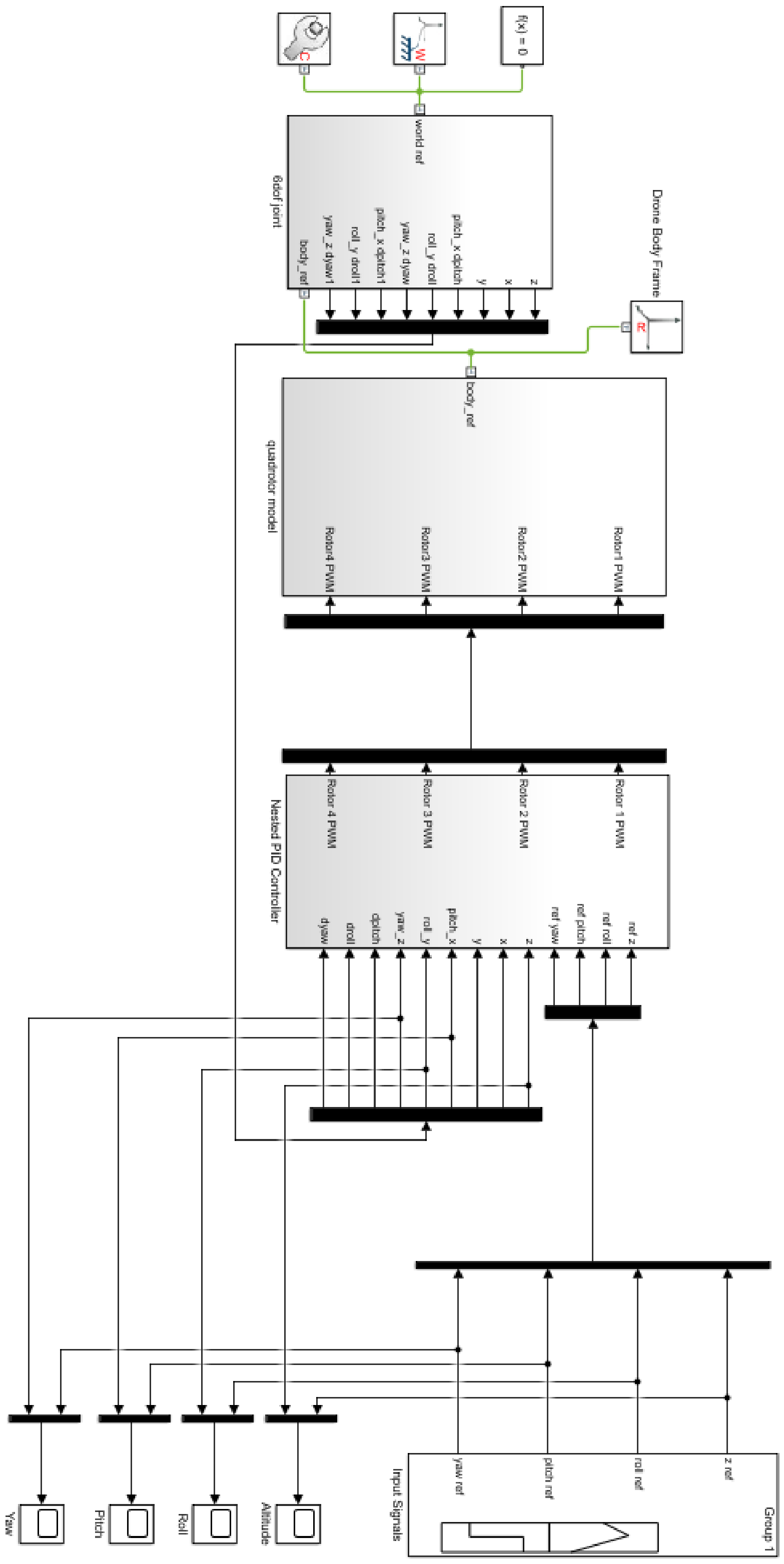


Figure 3.6: Block diagram of the proposed control quadcopter

For more details , each subsystem is modelized as follows

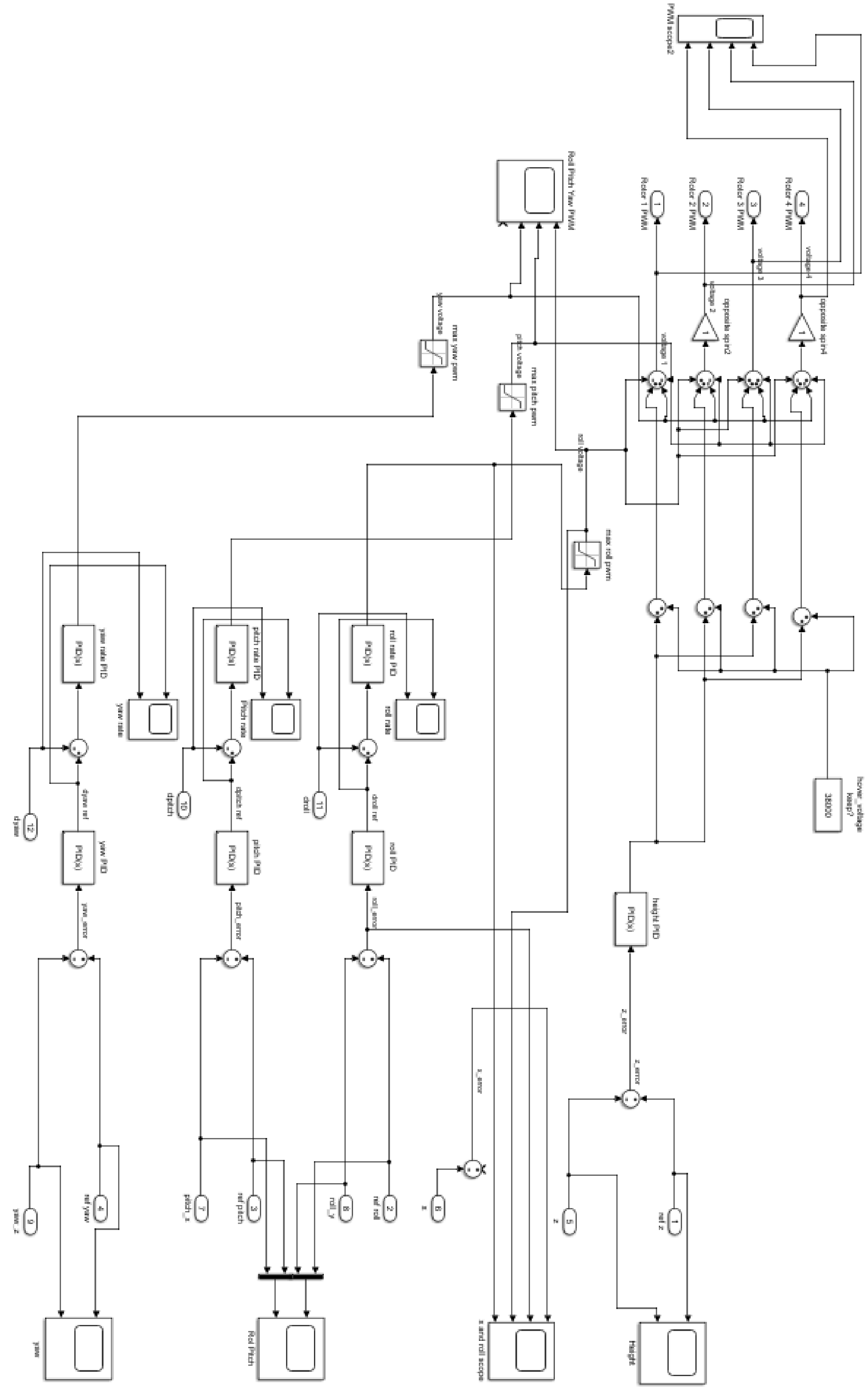


Figure 3.7: Block diagram of the PID Sub-system

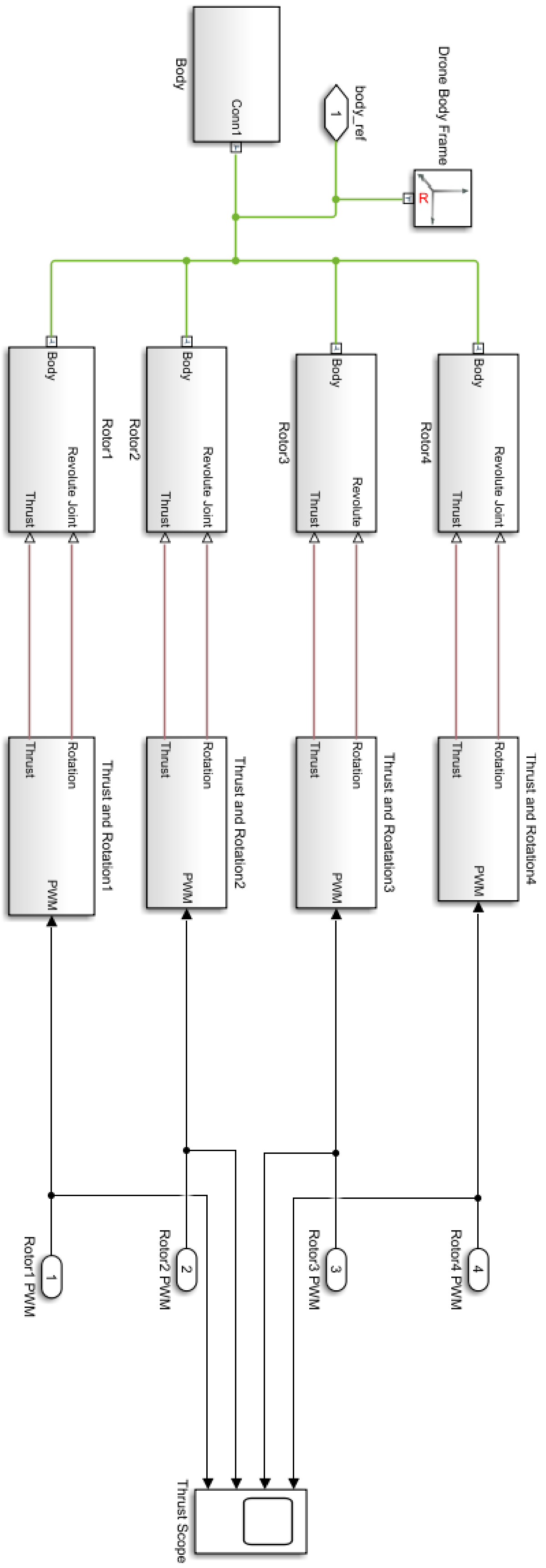


Figure 3.8: Block diagram of the quadrotor model sub-system

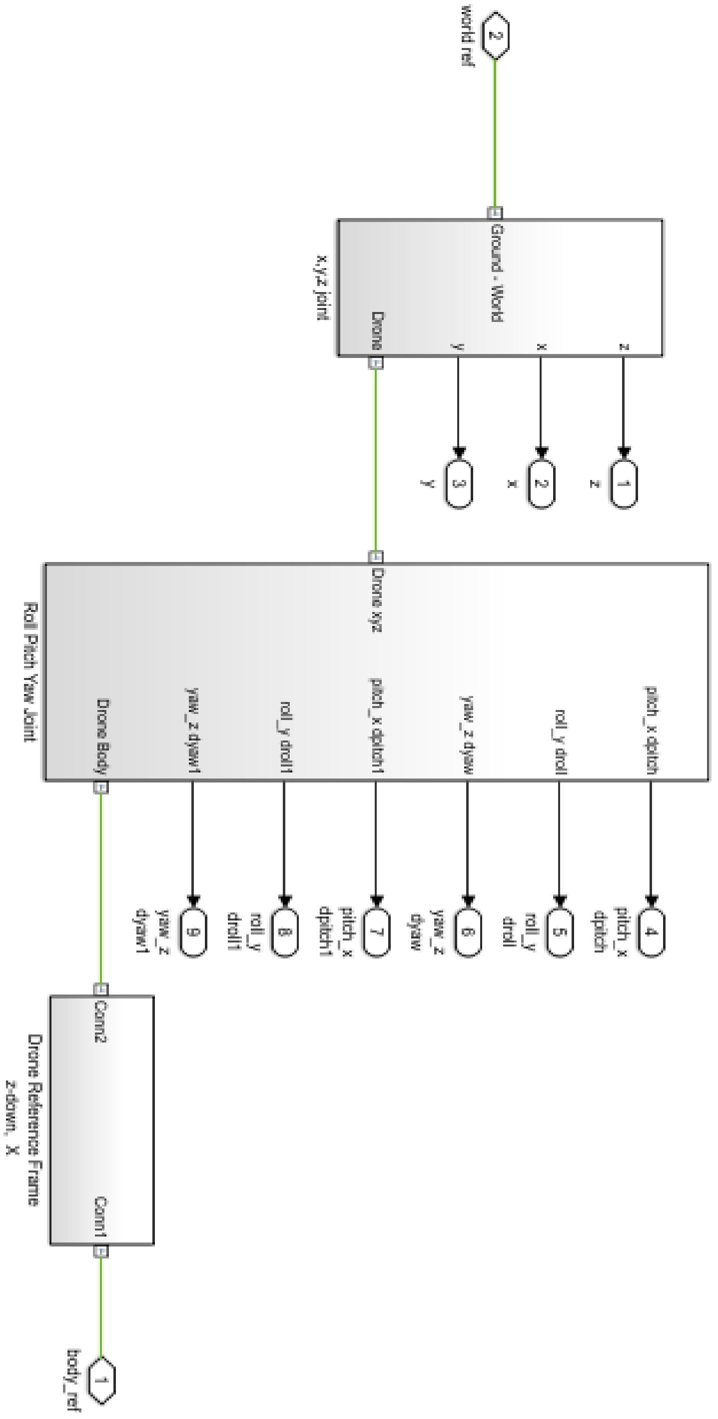


Figure 3.9: Mechanical joint sub-system

In the simulation , a given scenario is used in order to track altitude , pitch , roll and yaw and test their stability as well as the response time:

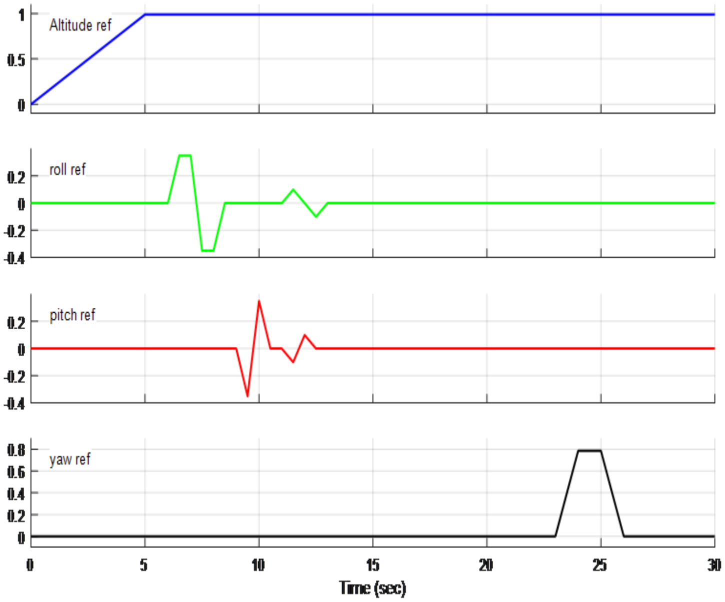


Figure 3.10: Proposed simulation scenario of Altitude , pitch , roll and Yaw angles

### 3.3.1 Simulation results

As mentioned earlier , to perform the best PID values, a tuning with different simulations is needed in order to get the optimal values. A set of different parameters are tested and summarized as follows.

- **Test set N°1**

Table 3.1: PID parameters for simulation N°1

| | Height | Roll | roll rate | Pitch | Pitch rate | Yaw | Yaw rate |
|---|---|---|---|---|---|---|---|
| P | 10000 | 2 | 150 | 2 | 150 | 2 | 70 |
| I | 0 | 2 | 200 | 2 | 200 | 0.5 | 8 |
| D | 500 | 0 | 1 | 0 | 1 | 0.1 | 0 |

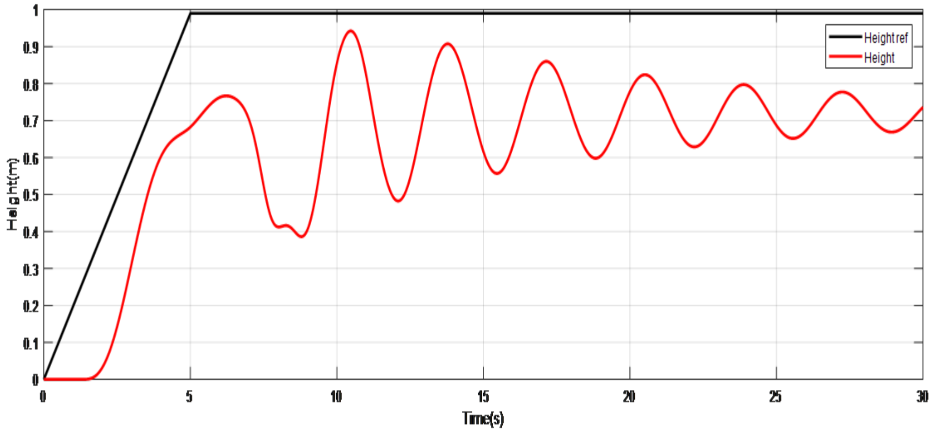


Figure 3.11: Comparaison between reference and simulated altitude (simulation N°1)

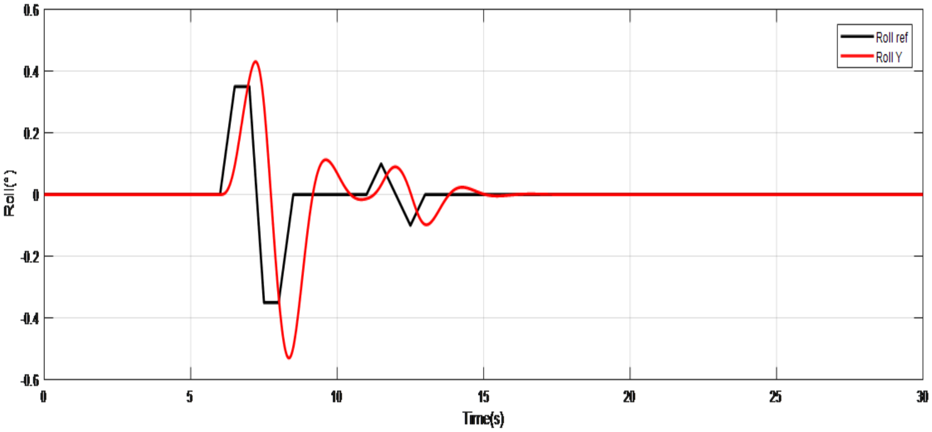


Figure 3.12: Comparaison between reference and simulated roll angle (simulation N°1)

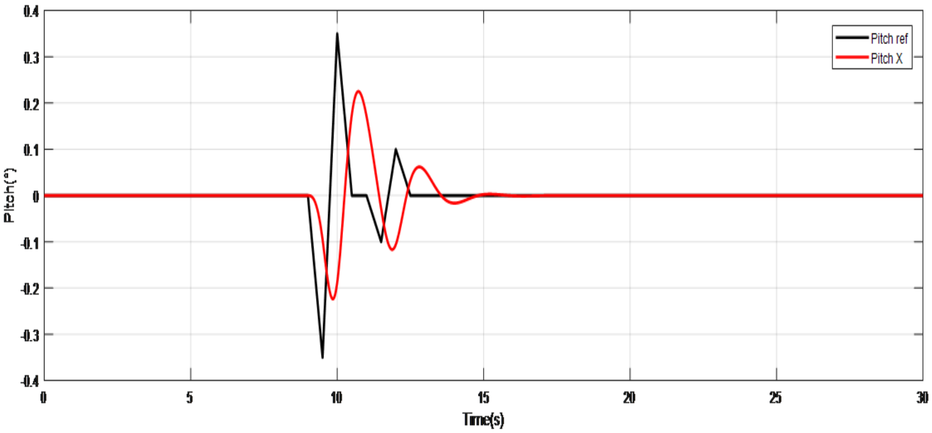


Figure 3.13: Comparaison between reference and simulated pitch angle (simulation N°1)

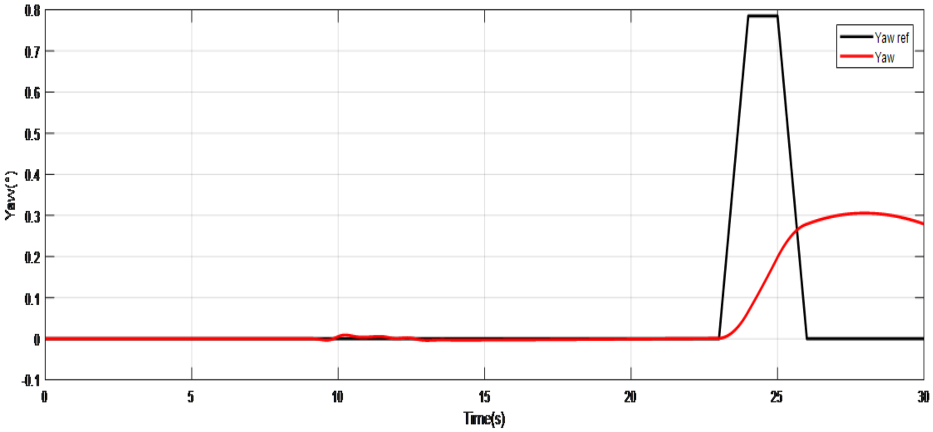


Figure 3.14: Comparaison between reference and simulated Yaw angle (simulation N°1)

- **Test set N°2**

Table 3.2: PID parameters for simulation N°2

| | Height | Roll | roll rate | Pitch | Pitch rate | Yaw | Yaw rate |
|---|---|---|---|---|---|---|---|
| P | 100000 | 70 | 1500 | 2000 | 300 | 200 | 200 |
| I | 100 | 5000 | 1000 | 70 | 600 | 2 | 20 |
| D | 10000 | 0.5 | 5 | 300 | 10 | 0.5 | 2 |

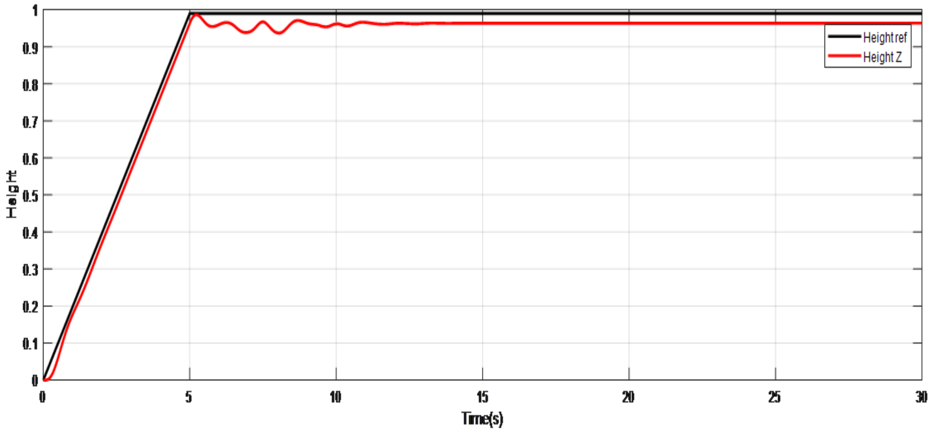


Figure 3.15: Comparaison between reference and simulated altitude (simulation N°2)

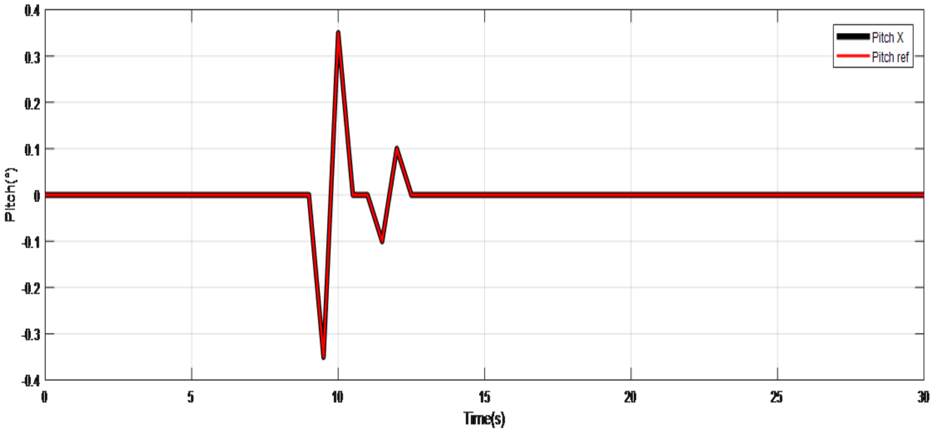


Figure 3.16: Comparaison between reference and simulated roll angle (simulation N°2)

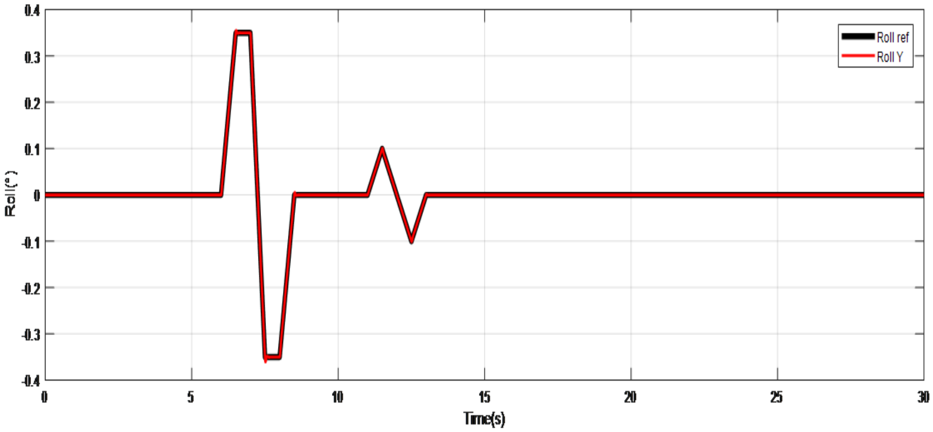


Figure 3.17: Comparaison between reference and simulated pitch angle (simulation N°2)

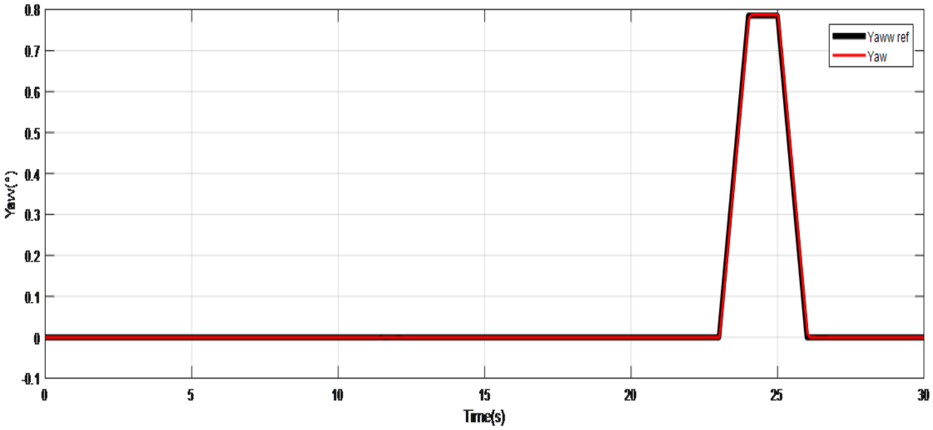


Figure 3.18: Comparaison between reference and simulated Yaw angle (simulation N°2)

- **Test set N°3**

Table 3.3: PID parameters for simulation N°3

| | Height | Roll | roll rate | Pitch | Pitch rate | Yaw | Yaw rate |
|---|---|---|---|---|---|---|---|
| P | 20000 | 6 | 250 | 6 | 250 | 6 | 120 |
| I | 0 | 3 | 500 | 3 | 500 | 1 | 16.7 |
| D | 10000 | 0 | 2.5 | 0 | 2.5 | 0.35 | 0 |

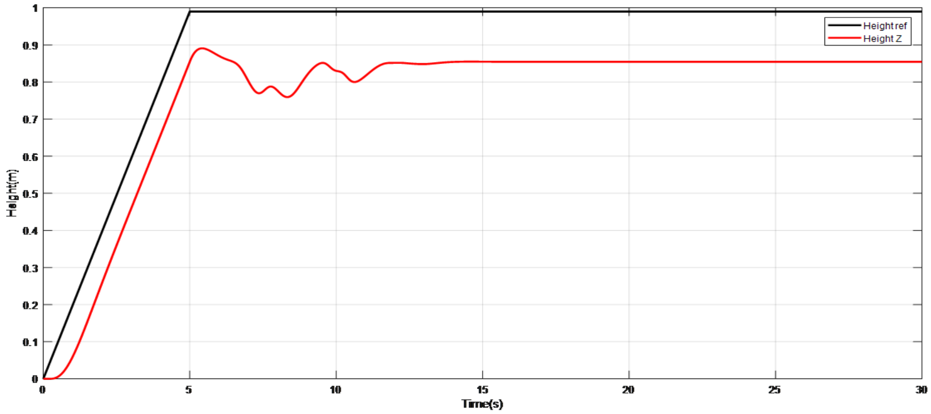


Figure 3.19: Comparaison between reference and simulated altitude (simulation N°3)

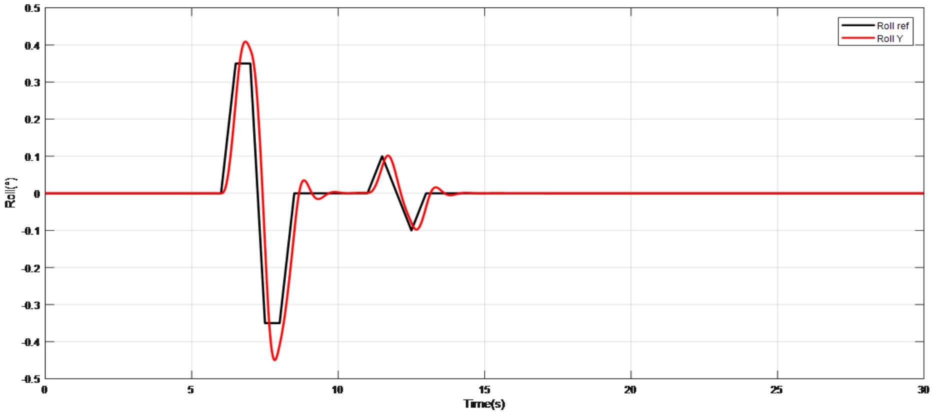


Figure 3.20: Comparaison between reference and simulated roll angle (simulation N°3)

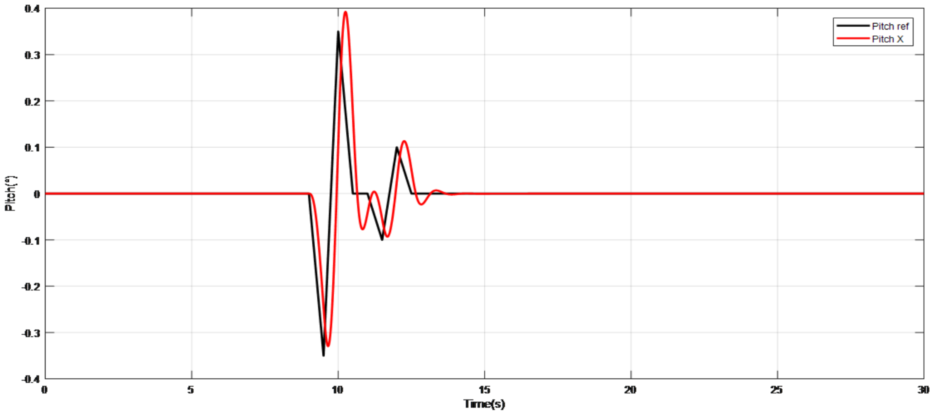


Figure 3.21: Comparaison between reference and simulated pitch angle (simulation N°3)

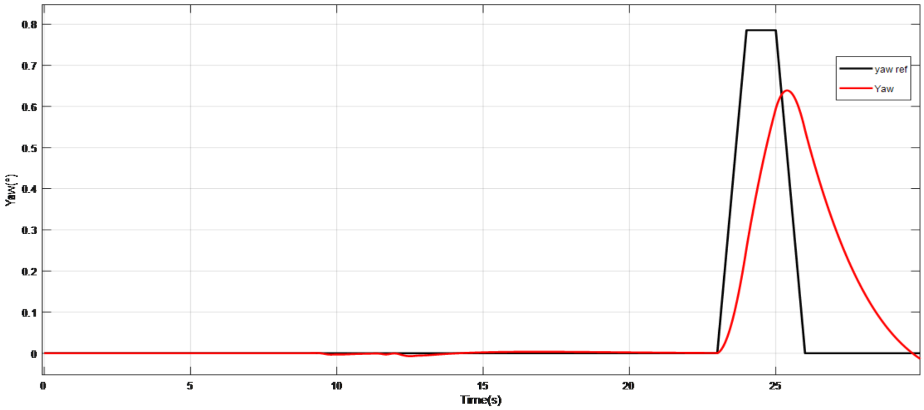


Figure 3.22: Comparaison between reference and simulated Yaw angle (simulation N°3)

## 3.4 Discussions

Based on the above mentioned simulations , we can notice that each term can give different infleunces for the mini quadcopter.

- P regulator determines how hard the flight controller works to correct error and achieve the desired flight path with sensitivity and responsiveness setting. Higher P gain means sharper control while low P gain means softer control. If P is too high, the quadcopter becomes too sensitive and tends to over-correct, eventually it will cause overshoots, and you will have high frequency oscillations. Lower P is used to reduce the oscillations, but reduce it too much and the quadcopter will start to feel sloppy.

- D gain works as a damper and reduces the over-correcting and overshoots caused by P term.

Like a shock absorber stops the suspension from being bouncy, adding D gain can “soften”and counteract the oscillations caused by excessive P gain, as well as minimizing propellers wash oscillations.

When D is too low, the quadcopter will have bad bounce-backs at the end of a flip or roll, and felling the worst experience of propellers wash oscillations in vertical descents. Increasing D gain can improve these problems, however, an excessive D value can introduce vibration in the quadcopter because it amplifies the noise in the system. Eventually this will lead to motor overheat and quad oscillation. Another side effect of excessive D term is the decrease in the quad’s response, this effect is often described as “mushy”.

- I term determines how hard the flight controllers works to hold the drone’s attitude against external forces, such as wind and off-centered centre of gravity. When I is too low , we might to correct the quad’s flying path a lot more with remote control sticks, especially when the throttle is active.

When I gain gets too high, the quadcopter will be overly constrained by this, and start to feel unresponsive. It’s similar to having a slower reaction and a decreased P gain. Excessive I gain in extreme cases can create a low frequency oscillation. In the real world, no two ESC’s, motors or propellers are identical, which provide different levels of thrust even when spinning in the same air.

When we do a punch out and immediately lower the throttle, one motor might increase and decrease rpm faster than the others, this will cause an unwanted dip movement. We increase I gain to “fix” these details in the flight performance. To avoid bringing in undesired “stiffness” to our quads with high I gain.

For the PI regulator we can see that the static error is eliminated (precision), the system is fast of course as long as the proportional action is used and the problem of overshoot still exists.

After using the PID regulator with the three actions, we notice that the derivative action eliminates the overshoot, that is to say stabilizes the system on the desired value, so at the end we have a fast, Precise and stable system.[51]

The standard value was chosen by taking into account the compatibility between the values in the simulations and in fact where there are many unknown effects of various types (winds, hurricanes or rains ...) and variable intensity this is what forced us to leave a margin between the real values and the values to be reached to be logical work and close to reality because ideal values are not realized.

Finally we can conclude that high gains of P, I and D together leads to a stable system but with high oscillations. In the other side, low values of P, I and D gains instable systems. As a conclusion of this, optimal values should be chosen carefully for optimal response with good stability and low oscillations .

## 3.5 Conclusion

In this chapter, PID controller is implemented in simulation and experimentally taking into account the full model of the proposed quadcopter. A Matlab/Simulink model is developed and different PID values are tested. The simulation leads to understand the how can each gain affect the stability of the mini quadcopter . Using two pid can reduce significantly the affect of the wind as a second factor that affect the stability in parallel with the given reference.

# General Conlusion

In this dissertation, we have touched the field of aeronautics (drones); from our topic which is simulated drone stability through the PID controller, we conclude that self-driving aircraft need a high degree of control in view of their working conditions, which depend on the climatic conditions of the flight area, where we find many different external influences, strong, sudden and not specific as variable winds speed, storms, rains ... etc. In this note, we got acquainted with the technology of PID control and its use in the field of autonomous flying.

We have noticed some deficiencies, which mainly lie in the accuracy of the measurement of error, which is the physical amount (angle) in addition to the difficulty in calculating the Ki, Kp, Kd by experimental method which are fundamental constants so that the automatic controller can know the optimized values that make the error rate 0 or close to it and restore the stability state quickly, accurately and without vibrations.

Some conclusion can be extracted from this dissertation :

- The mathematical modeling is very complicated and some simplifications should be taken into consideration in order for modeling the dynamics of the quadcopters.
- Different control schemes can be found in literature to stabilize the movement of quadcopters . However, it is better to consider basic ones such as PID because of its simple implementation and reliable responses .
- Several factors should be taken into account in the realization of the quadcopters. Type of the frame , quality of materials and their weights and the quality of electronic components should be chosen carefully for best flying experiences.

Finally , we propose various possibilities of continuation of the project for future works such as :

The first step is to reach a more precise control technology in measurement and we suggest using the very sensitive optical sensors like the LDR in addition to using the mathematical method in calculating which inevitably will be more accurate. to expand degrees of freedom of the quadcopter and the number of its aerodynamic movements by controlling the direction of propellers are what we can even turn the drone upside down by defining the face and inserting an algorithm, always with optical sensors.

We suggest studying the replacement of the PID technology with predictive control due to the sensitivity of the system represented by the drone, depending on the factors that suggest the occurrence of a disterbance, and this is what falls within the framework of artificial intelligence that represents the subject of the time in the field of research.

We suggest studying how to use a single central motor connected to a pinion and a belt that recycles all propellers as electromechanical solutions to reduce energy consumption and reduce losses resulting from the large number of motors that contain a lot of wings known excessive reactive energy consumption and that also requires the presence of capacity to compensate this energy in addition to the large number of conductors and ESC, which all contain internal resistors, increases energy losses and increases the weight of the system, which requires greater torque, which means greater consumption and more losses.

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