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Theme

Numerical Model Development of a Transformable Quadrotor

Publicly defended, on 09/27/2021, in front of the jury composed of:

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I would like to offer this work to my mother first, for supporting me through my education path and being so patient with me through the whole period of the preparation of this work, I also want to offer this work to my grandmother and uncle and thank them for being on their nerves through this period.

I also would like to offer it to my parents, my dad especially as well as to my sisters and brother.

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ملخص:

تزداد الحاجة إلى مركبات الطائرة بدون طيار أكثر فأكثر كل يوم نظرًا لقدرتها على الوصول إلى الأماكن والقيام بالمهام التي يصعب على الإنسان الوصول إليها والقيام بها يمكن للطائرة بدون طيار أن تتحدى بعض العقبات مثل العمر القصير للبطارية أو الظروف البيئية الخاصة (العوائق ، الطقس القاسي ...) أو مجرد التحرر من درجات الحريةالست التي تعيق تحركها في كل اتجاه.

يمكن لهذه الظروف الخاصة لبيئة عمل الطائرات بدون طيار أن تمنعها من القيام بمهامها أو العمل بشكل صحيح و تؤدي حتى إلى فشلها التام لتجنب مثل هذه الأضرار ، كان لدى العلماء والمهندسين الرغبة في صنع نوع جديد من الطائرات بدون طيار ، الطائرات بدون طيار القابلة للتحويل.

الطائرات بدون طيار القابلة للتحويل أو الطائرات بدون طيار القابلة لإعادة التشكيل هي الطائرات بدون طيار التي يمكنها تغيير شكلها من أجل التكيف مع البيئة الخارجية.

اخترنا دراسة الطائرات بدون طيار القابلة للطي بشكل أكثر تحديدًا ، والتي تدور أذرعها الأربعة أفقيًا. باستخدام كل من النماذج الرياضية والرقمية لتمثيل التكوينات المختلفة للطائرة الرباعية القابلة للطي ، حصلنا على نتائج مختلفة قليلاً كما كان متوقعًا، بسبب استخدام نموذجين مختلفين. ولكن الأشياء المشتركة حول النتائج هي أن نتائج كلا النموذجين تمثل حالات ثابتة للطائرات الربعاية بدون طيار في تتبع مساراتها وكلا النموذجين إلى اتباع نمط المسار المعطى كمدخل.

Abstract:

Unmanned Ariel vehicles are needed more and more everyday due to their ability to reach places and do tasks that are hard for human to reach and to do.

Drone can face some challenges such as the short life of the battery or the environmental special conditions (obstacles, rough weather…) or just to be liberated from it six degrees of freedom.

These special conditions of the drone working environment can prevent it from doing it tasks, functioning correctly or even lead to it total fail.

To avoid such damages scientists and engineers had the urge to make some new kind of drones, the transformable drones.

Transformable drones or reconfigurable drones are the drones that can changes their morphology In order to adapt with the external environment.

We chosed the study of foldable drones more specifically horizontally rotating arms quadrotor. Using both mathematical and numerical models to represents the different configurations of the foldable quadcopter, we obtained little different results what was expected due to the use of two different models but the common things about the results is the results of both models represent steady states of the quadcopter and both model results tend to follow the pattern of the trajectory given as an input.

Résumé :

Les véhicules Ariel sans pilote sont de plus en plus nécessaires chaque jour en raison de leur capacité à atteindre des endroits et à effectuer des tâches difficiles à atteindre et à accomplir pour les humains.

Le drone peut faire face à certains défis tels que la courte durée de vie de la batterie ou les conditions environnementales particulières (obstacles, mauvais temps) ou simplement se libérer des six degrés de liberté.

Ces conditions particulières de l'environnement de travail du drone peuvent l'empêcher d'effectuer ses tâches, de fonctionner correctement ou même de conduire à son échec total.

Pour éviter de tels dommages, les scientifiques et les ingénieurs les scientifiques et les ingénieurs ont fabriqué un nouveau type de drones, les drones transformables.

Les drones transformables ou reconfigurables sont les drones qui peuvent changer de morphologie afin de s'adapter à l'environnement extérieur.

Nous avons choisi l'étude de drones pliables plus précisément à bras quadrotor à rotation horizontale. En utilisant à la fois des modèles mathématiques et numériques pour représenter les différentes configurations du quadcopter pliable, nous avons obtenu des résultats peu différents, ce qui était attendu en raison de l'utilisation de deux modèles différents, mais les points communs des résultats sont que les résultats des deux modèles représentent des états stables du quadcopter et les deux résultats du modèle ont tendance à suivre le modèle de la trajectoire donnée en entrée.

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General Introduction

Drones previously used in military services only, had a rapid growth of civilian use also, in the last years. Drones proved to be efficient in several domains taking examples of film-making and photography, as they are nowadays used to take shots from different angles with a low cost. In addition to that, search operations, air transport and delivery of goods represent important applications of the drones also. Drones in different sizes proved to be so useful to people, as human themselves have limited ability when it comes to extreme situations in rescue inspections or filming behind a cliff.

The diverse use of this aerial vehicle and it low cost, accuracy and ease to use, had the attention of a lot of searchers and laboratories, to make this aerial robot better and more efficient.

However, despite the large use that the drone has accomplished, it still did not reach it full potential, what is caused by the limitation of the drone's mechanical structure and fixed shape. The drone rigid structure makes it very difficult to small spaces with changing surface, without bending in order to size down it body shape .

When it comes to new unknown spaces with inconvenient trajectories, and changing, unstable environments, such as narrow gaps and during a rescue missions as the changes are unpredictable, the classical fixed drones became unreliable. Especially with the necessity of assuring a stable flight and decreasing the battery consumption in order to save energy.

Due to the changing state of the practical environments, engineers and scientist had the urge to think of an adaptive version of the drones. Configurable drones with different types and sizes represents an interesting solution of the concerning problems facing the classical drone .

The quadrotor represents a large portion of used drones in laboratories due to it simple mechanical structure. This structure can be easily modified, what pushed a lot of researchers to use the quadrotors to be the adaptive version of the drones. Transformable quadrotors can perform critical and dangerous tasks thanks to it adaptive morphology that gives it the ability to negotiate vertical and horizontal narrow gaps and even inspecting sensitive spots.

When it comes to testing and having experiences on systems and their controls, it is considered a bit risky to use the real system. Especially if a system represents a complex phenomena such as the drone. In addition, the non linear nature of the drone makes it easily lose it steady state and eventually fail or crash. For that, considering the modeling of such system is a better alternative in order to to save time and the equipment at a low cost.
This thesis is taking the study of the transformable quadcopter as a subject, by using both numerical and mathematical models to best estimate and compare the results.

The first chapter is having a brief history of drones, classification of different drones, than their applications, next controls of transformable drones, the quadrotor models and finally the challenges facing the transformable drones and our contribution to knowledge. The second chapter is mentioning the dynamics acting on the transformable quadrotor and establishing the mathematical model. The third chapteris having definitions the mathematical model description and principally describing the conception of the numerical model. The fourth chapter is having of the peices used in the numerical model on simulink and displaying the obtained results and discussing them and finishing by a general conclusion.

Chapter 1

State of art

Contents

1.1 Introduction

UAV[1] used in the past in military and nowadays even by civilians to best serve our day to day needs. The drones proved efficiency in saving time, giving new solutions to real life problems what wasn't possible before and having useful applications such as aerial photography and filming, aerial mapping, inspections and rescue operation aerial surveillance [1] [2] and delivery, being such an interesting technology with useful functionalities made it an interesting subject to study. This subject is handled by several papers such as [3] [4] and conferences as [35], to assure efficient flight autonomy and get the best performances that the drone can give, from multiplying it rotors [5] to applying different control algorithm on it [6] [7] [8], changing it's structure and even making it animals look like all of that in order to make it cover the biggest range of services that it can offer and applications that can done by a drone.
Foldable drones are a great case to study not just because they make interesting applications and maneuver in critical structures but they also represent the solution of the principal problems that the classical fixed has to face which are the limitation of the structure and energy consumption.

So in this chapter a brief history of the drones will be presented after the definition of the Unmanned aerial Vehicles as well as the types of the transformable drones represented in the literature and the the different controls applied as well.

In order to keep a constant understanding of the over all thesis, it is important to keep knowledge of the next definitions that represent the main terms used in the rest of the chapter as well as the keywords of this work:

- Drone what once meant a male bee in the old English according to Oxford dictionary, today is used to refer to the UAV Unmanned aerial Vehicle or uncrewed aerial vehicle which represents a remotely controlled aerial aircraft or in some cases automatically controlled. In other words they are planes witch are different in size and shape with no human supervision or remotely supervised.
- Rotorcraft are aerial robots that basically use rotors to fly, such as quadrotor with four rotor the hexarotor with six rotor and the octarotor with eight rotors as well as the helicopter and gyrocopter.
- Quadcopter is a UAV or a drone with four rotors that can be either in a plus (+) or X configuration controlled by an algorithm that balances between the rotors rotation speed in order to maintain that stable hover of the drone.
- Configurable drones are the UAVs in witch there structure is rigid and fixed that can't change during any level of the drone's operation life time [9].

Drones represent quit an interesting topic but how far back does it history go?

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[1] Unmanned aerial Vehicle

1.2 History of drones

Starting from 2010 the world witnessed a big leap in the in the UAV field as it became available for civil use after it was limited to the military only and it history goes back to the 18^{th} century. The first recorded on operation attempt of an Unmanned aerial vehicle goes back to 1849 when Austrians thought of lunching a remote attack on Venice using 200 unmanned balloons stuffed with explosives as showed in the figure 1.1 . But lucky for the Venetians and due to the sudden wind change, only one hit the right target, even that there was several attempts before such as the Leonardo da Vinci screw, Archytas din Tarantas but the remote balloons are the first successful attempt to be recorded [10].

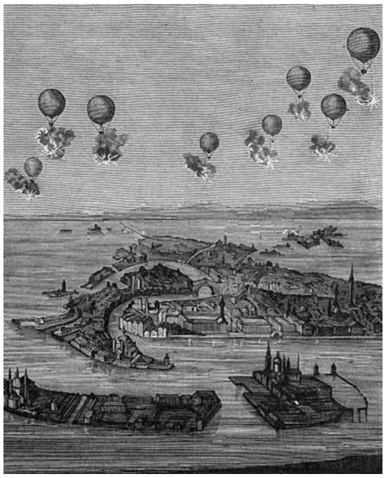

Figure 1.1: First attempt of a drone [10]

Several attempts followed the remote balloons to create efficient UAVs such as the wireless balloon of Nikola Tesla in 1900 [10] and the first thing closed to a quadrotor in 1907 as the brothers Jacques and Louis Breguet hands made an early example of their plus (+) configuration gyroplane, using a 49.8 KW in power motor placed in the center and rotating all four rotors that were placed in the end of the arms [11], it managed to fly 0.6 meters high with the need of four men in controlling role to keep it stable figure 1.2.

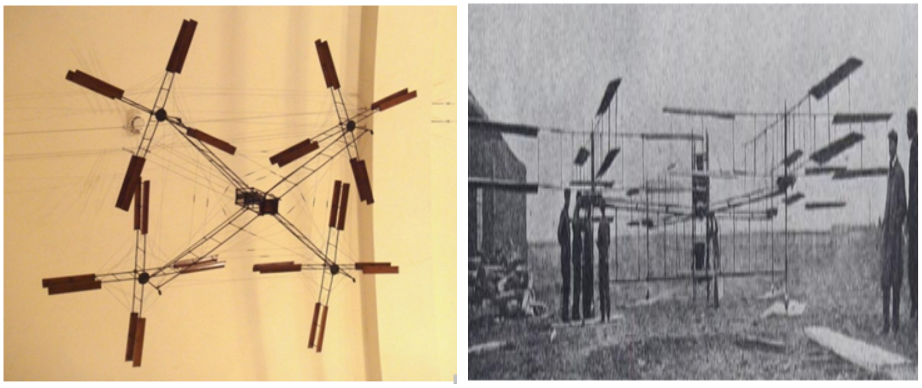

Figure 1.2: Breguet-Richet Gyroplane No.I [11]

With the rise of the First and Second World War a new kind of UAV appeared the fixed wings drones,an unmanned version of war planes.Mentioning the Ruston Proctor Aerial Target in 1916 developed by British engineer Archibald Lowthe Kettering Bug in 1917 the U.S. Army [10]. In the 1930s, the U.S. Navy began experimenting with radio-controlled aircraft successed to make De Havilland DH-82B in 1933 In 1935, the British developed Queen Bee, a radio-controlled target drone next figure 1.3 demonstrate it launch.
The drones have a quit interesting history, but how does that reflect it development today?

Figure 1.3: Launch of a DH.82 Queen Bee (mother of drones) target drone (1941) [49]

1.3 Classification of different drones

UAV is a vast field that can be classified by different into categories according to different criteria (size, application, mission...), adopting the next classification schema of the different types of the UAVs, focusing on the transformable drones represented in the next figure 1.4 that is inspired from the thesis[9].
UAVs are either hybrid what makes them either aerial and aquatic or aerial and surface drones, or in most cases only aerial everyone one of them has either fixed wings or rotary wings. As this thesis is considering transformable quadrotor, this classification is considering rotary wings classification. Rotary wings or multi rotors drones has three main subcategories which are the quadcopter that refer to the drones with four rotors hexacopter are the drones with six rotors,and the octocopters are the drones with eight rotors.
Quadcopter can be either reconfigurable or not but as the transformable quadrotors are reconfigurable we'll be interested in following this classification path.
Reconfigurable Quadcopter are devided into five subcategories which are multilinks quadcopter, foldable quadcopter, extendable arms quadcopter, tilting rotors quadcopters and deformable body quadcopter.

These categories will be taken explicitly in the section that fellows and discussing the work of other authors of the relevant categories to our subject.

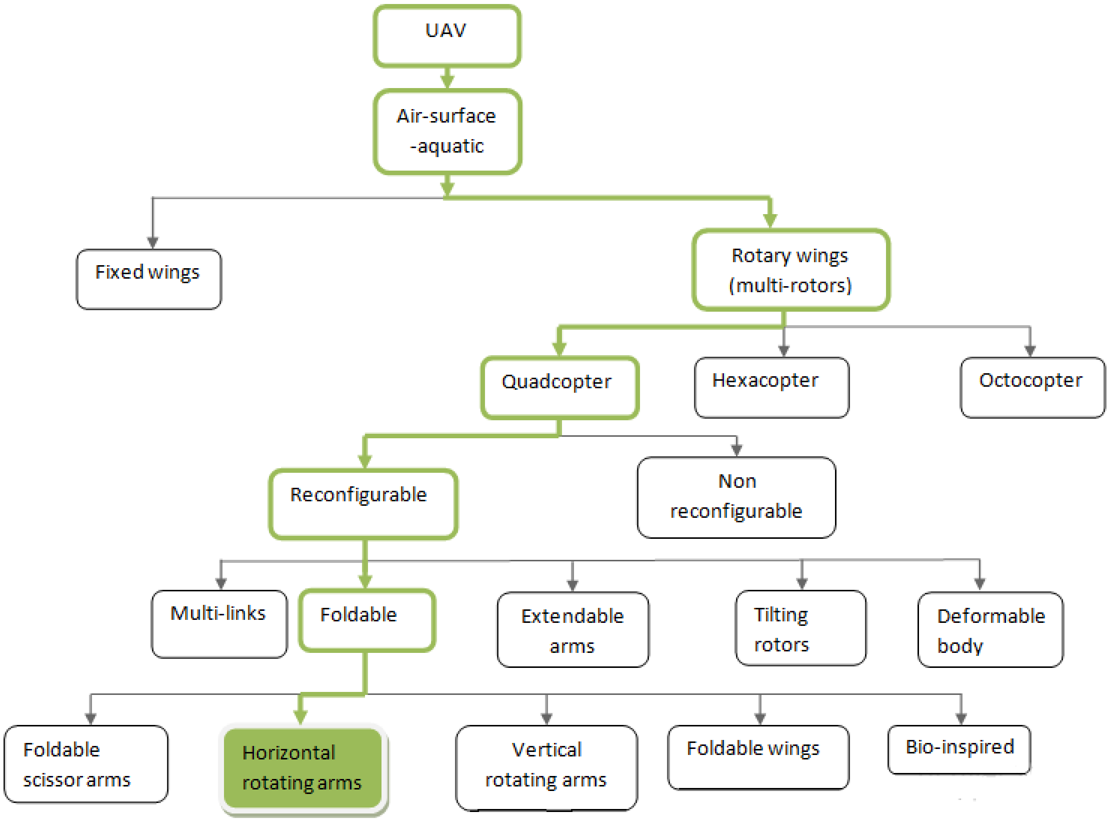

Figure 1.4: UAV categories classification schema

Configurable drones

Configurable drones or called transformable drones are advantageous when it comes to navigating through critical structures such as narrow gaps, changeable and unstable trajectory, and that is due the adaptive configuration of the drone to the trajectory represented.
These kinds of drones have some slight changes in its physical structures that give the drone more structural freedom to make it either a multi functional drone or to improve the control over the drone. reciting some examples such as the folding arms drones, Hybrid terrestrial-aerial drone such as presented by Kossett et al. [12] [13] or Hybrid air-underwater drone and even animal imitating drone as mentioned in the thesis[14].As this thesis is taking part of the configurable quadcopter, this category will be exploited by the following.

1.Extendable arms drones Extendable arm drones are the quadrotors that have the ability to change their body dimensions behaving longer or shorter arms as shown in the figure 1.5 in order to navigate through limited in size spaces these kind of transformable quads represent other advantages represented in the ability of the drone to pitch roll and yaw without need to modify the rotors speed and that by varying the length of the arms in front/back or left/right in case of pitching or rolling respectively and varying the length of the same axe arms with the opposite rotors for yawing [15] [16].

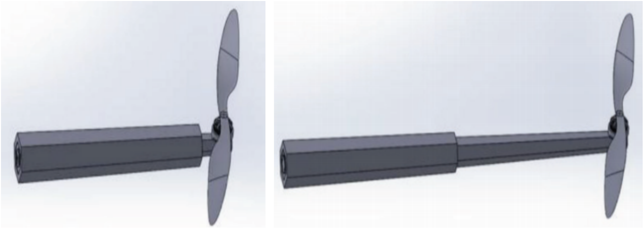

Figure 1.5: The mechanism of the extendable arms drone

An other kind of the extendable arms drones are the Sliding Arm Quadcopters as represented in [17], the authors considered using a plus (+) configuration quadcopter as shown in figure 1.6. Each opposite two rotors are linked by the same arm so if one rotor slides towards the body center, the opposite rotor would be moving away and vice-versa what variates the center of gravity and inertia in the dynamics of the body in consequence. Using a belt driven by a servomotor that allows that motion as shown in figure 1.6 and PID[2] controller for both attitude and position control.

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[2] Proportional Integral Derivative

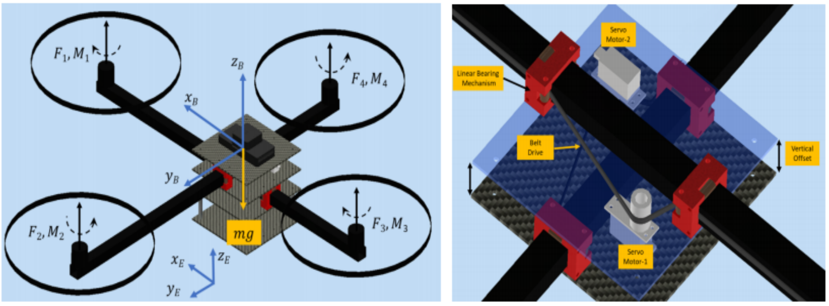

Figure 1.6: Sliding Arm Quadcopter

2.Tilting parts drones This kind of drones have as a main functionality to reduce their size as they are used to maneuver limited spaces or spaces with obstacles what is considered a complicated or impossible task to the classical drones. This type of UAVs concerns the drones that we have found in the literature under different names as: tilting propeller drones, tilt wing drones, tail-sitter drones and convertible drones [18] which is can be mainly divided into three subcategories: tilting arms drone, two axes tilting drone, Hybrid Vertical Take-Off and Landing, and tilting body drone.

a. Tilting arm drone

As a solution for decoupled attitude and position tracking,caused by the changing the thrust direction within the air frame the thesis[50] suggests the Tilting arm drone, figure 1.7 in order to have better maneuvers in which the arms rotates independently around it self giving the quadcopter the possibility to hover using more than just the fundamental angles.

Figure 1.7: Tilting arm drone [51]

b. Two axes tilting drone

Tilting rotor drones relative to two axes [19] [20] this drones have their tilting arms using a servo motor linking each arm to the body just like the previous quadrotor. In addition it also has a smaller arm fixing the rotor, perpendicular to this arm that it self tilts giving the drone more freedom to manoeuvre vertically as showed in figure 1.8. Same goes for the work in [21] [22].

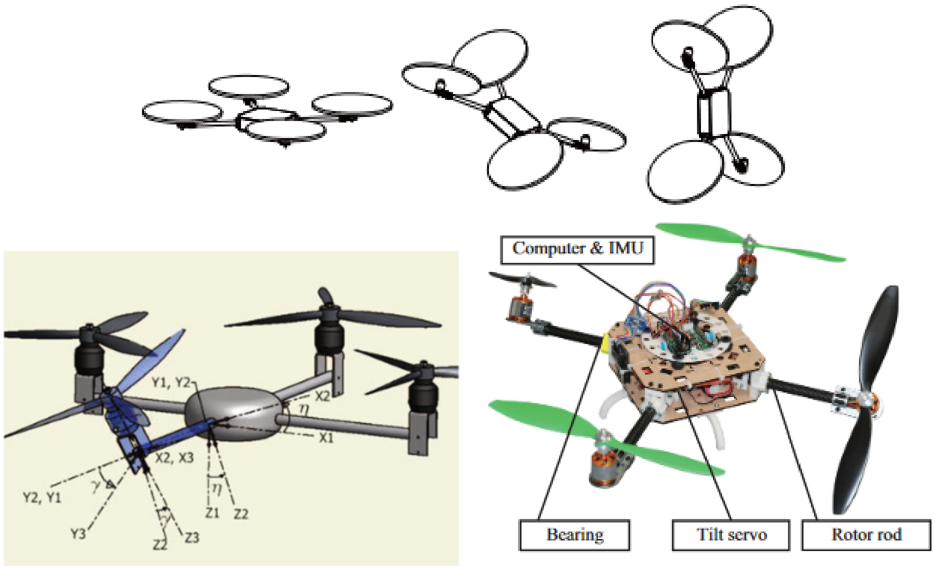

Figure 1.8: Two axes tilting drone [52]

This particular ability of this quadcopters, that focuses on the stability during the flight. Like in the case of figure 1.9 which uses a servomotor and a string at each arm pulling the rotor around the horizontal axe, as these mechanism are little complex to realise they consume more energy than the classical quadrotors and even physically heavier.

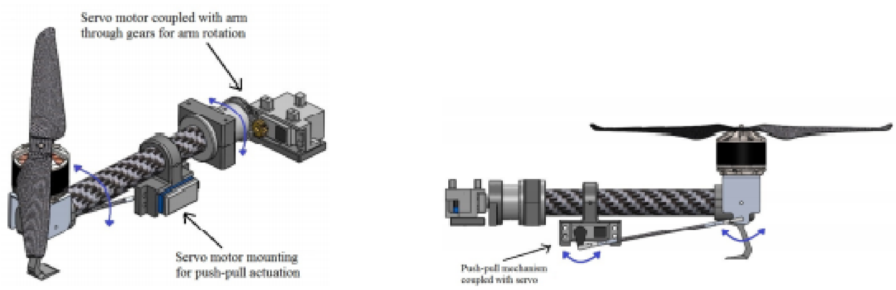

Figure 1.9: Two axes tilting drone [53]

c. Hybrid tilting drones

Hybrid VTOL[3] or HVTOL, they are basically fixed wings drones that can be twisted into a quadcopter as shown in the figure 1.10 as their wings can rotate in order to fly and land vertically, what gives the drone both horizontal and vertical flight configurations such work can be found in [23] [24] [25].

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[3] Vertical Take-Off and Landing

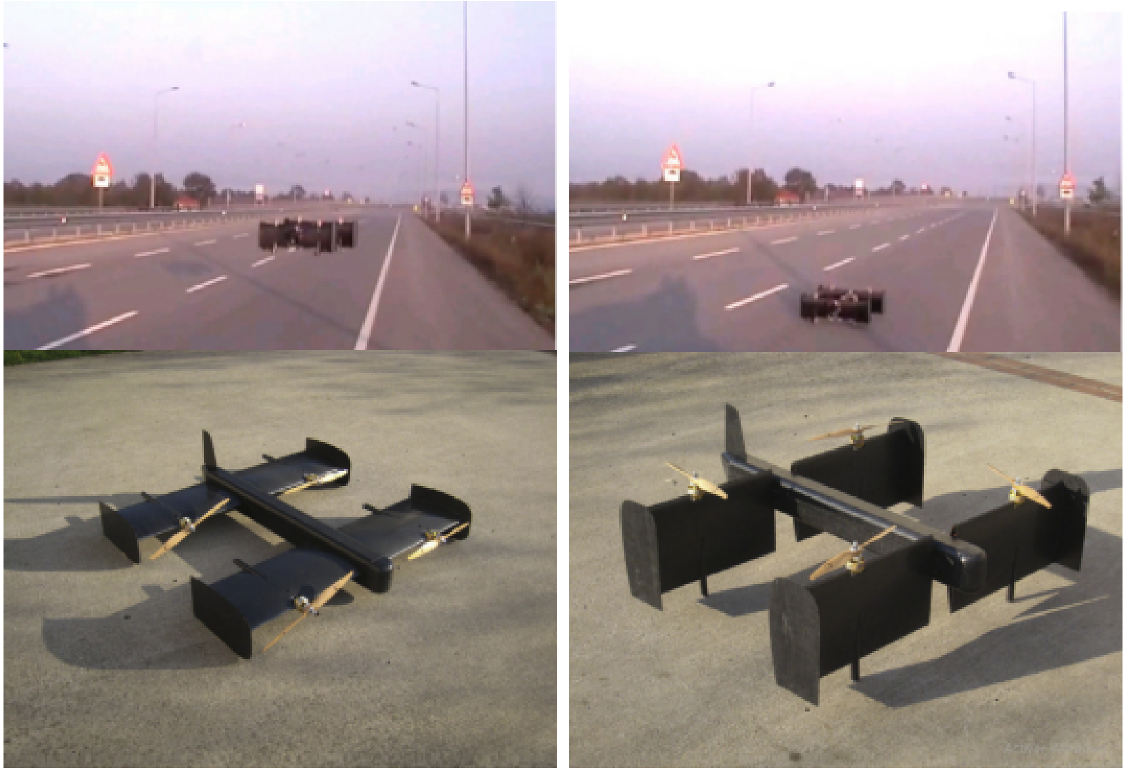

Figure 1.10: HVTOL drone [23]

d. Tilting body drone

This type of drone using a PID for the control in the thesis[26] and tilts using either a servomotor fixed in the body center in the case of [27] and [28] or by the rotors rotation as the next figure 1.11 shows, what is similar to the tilting rotors drones, and giving the quadrotor more freedom the quad a vertical configuration flight however this way the quad consumes a lot of energy.

Figure 1.11: Tilting body drone [28]

3.Foldable drones This kind of configurable drones, fold in order to reduce their

body size and to make their morphology environment adapted. Foldable drones have also several advantages such as optimizing energy, increase precision and endurance and make the system over-actuated.
This kind of transformable drones can be divided in several types, such as Bio-inspired drones, Foldable drones with vertical rotating arms and Foldable drones with vertical rotating arms.
As our study subject the foldable quadcopter, which falls into the foldable drones category, we will explore this category next and in which of it subcategories does our drone belong.

a. Bio-inspired drones

Are drones with a physical configuration inspired by animals such as insects as shown in the figures [8] and [9], birds [3] and even bats, in order to adapt these animals capacities of maneuvering in complex structures on the drone prototypes as represented on the figure 1.12 and 1.13 as did the authors in their work [30] by making a prototype that mimics a bat the bat maneuvers and what gives the UAV more positions and more body adjustments but just like the real bat as presented also by the work [54] and shown in the figure 1.14 what makes one of the biggest challenges facing this kind of UAV is the the nonlinear nature of the forces that act on it what makes flying it not an easy task to do.

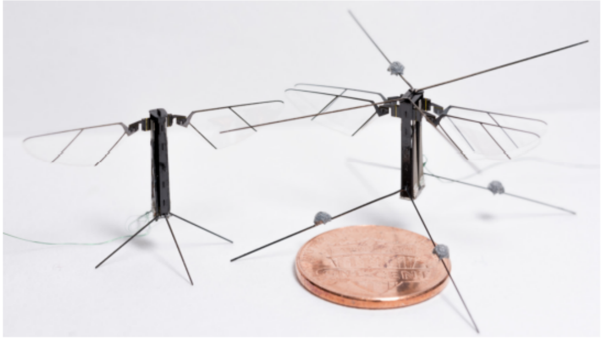

Figure 1.12: Insect-inspired drone [55]

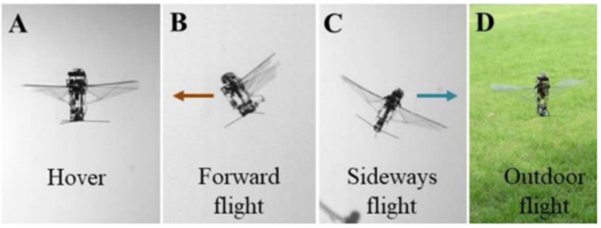

Figure 1.13: Insect-inspired drone [56]

Insects inspired UAV on the other hand focuses more on energy optimisation in the work [31]

Birds inspired prototypes represented in the works [34], [31] and [32] in which the author illustrate the folding wings movement and made a mechanism similar to the birds wings motion in order to reduce the drone size as presented in the figure 1.15 and that causes the increase of the drone speed due to the decrease of the friction facing the drone. most of these drones represent a great advantage as they are harmless to human unlike the other drones but most of these kind of drones are still limited in weight lifting and speed

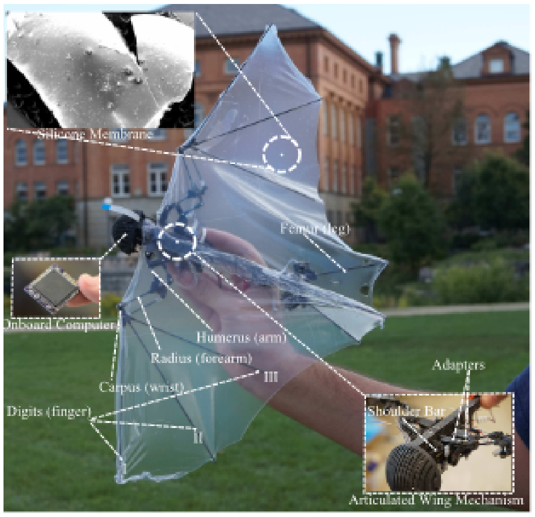

Figure 1.14: Bat Bot (B2) [54]

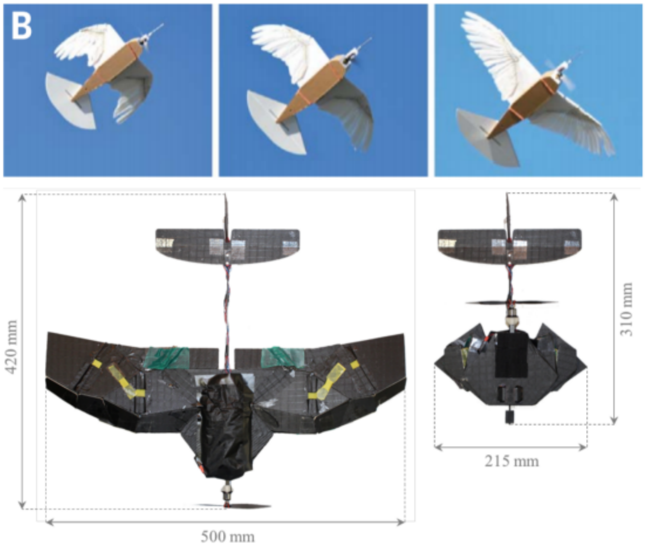

Figure 1.15: Bird-inspired drone, left [63] and right [62]

b. Foldable drones with vertical rotating arms

This type of transformable drone has the arms proportionally to the horizontal axe using either strings linked in the bottom of the quad pulling in the arms or a servo motor rotating each arm downwards in both cases the mechanism under the thrust decrease condition in other words when ever the thrust drops the arms rotates therefore this kind of mechanism needs precision and consumes a lot of energy. Vertically around the horizontal axis, using a spring mechanism or a servomotor between each arm and the body allowing the quadrotor to yawn until reaching a vertical position what it is considered an impossible task in the classical fixed arms quadrotors, giving the drone more freedom to manoeuvre vertically as shown in the figure 1.16 of the work [33], therefore this type consumes a lot of energy and requires a lot of precision.

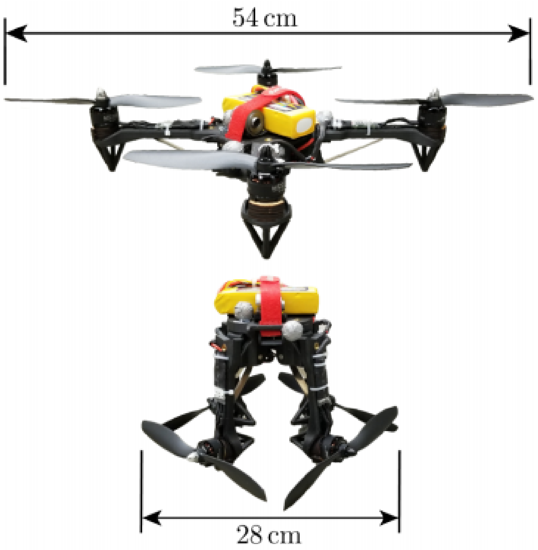

Figure 1.16: Vertical rotating arms drone [33]

c. Drones with horizontal rotating arms

Horizontal rotating arms gives the ability to the quadrotor to navigate in narrow gaps and caved spaces where each arms dependently rotate around the z axe giving the drone the ability to change it morphology when crossing a gap or an impended space.

Horizontal rotating arms, rotate either dependently as it is the case in figure 1.17 where a servo motor controls the crossing arms rotation [57] or as it the case in figure 1.18 where the four arms rotations are coordinated to pivot using a servomotor and strings that pulls the arms to turn from being one parallel to an other into being aligned folding in 230ms and unfolding in 310ms [58].

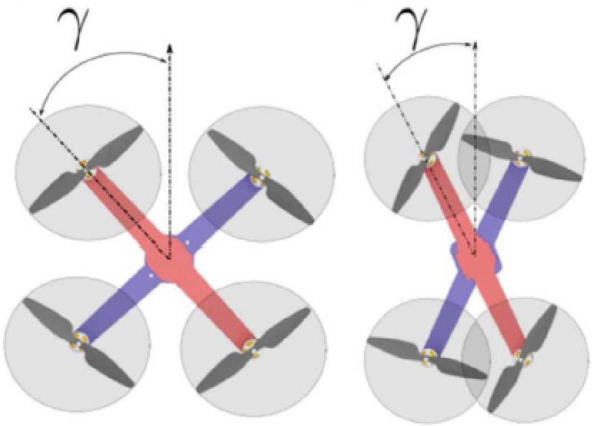

Figure 1.17: Sesor horizontal rotating arms drone [57]

This type of quadrotor represent the advantages of avoiding the collision of the drone arms in case the gap does not fit the original state of the quad but it has some disadvantages as it only folds at a speed of 2.5m.s and it loses it steady state while folding that is why it makes critical to respect the folding and unfolding time as well as the speed that are mentioned previously.

Figure 1.18: Horizontal pivoting arms drone [58]

An origami inspired pocket sized prototype developed by Stefano Mintchev and D. Floreano that can be fold using a magnet when the propellers aren't rotating causing the quad to fold and unfold when the propellers are rotating. as the figure 1.19 shows.

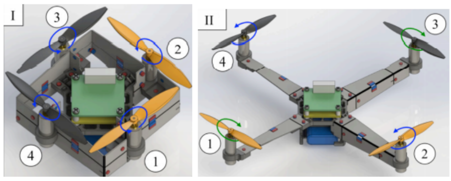

Figure 1.19: Origami drone [59]

As for other studies they choose to work on horizontal rotating arms quadcopter using a servo motor between the body and the arms in order to have an independent rotation yet convenient rotation that makes it easy to change from a configuration to an other.

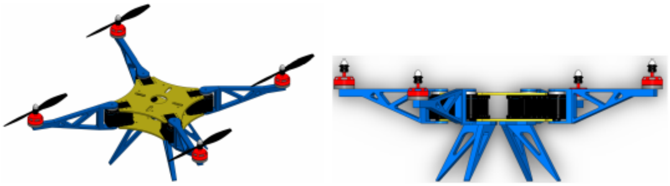

Figure 1.20: Horizontal rotating arms [34] [46]

In [36] the authors choose to work on such a prototype using backstepping control otherwise the authors in [37] [38] used LQR[4] to command the dependent morphology of the quadcopter.these quadrotors represent a new way of the drone to function but it still keeps the disadvantages of a classical quadcopters which are the limitation in the movement freedom that are represented in the tilting angles of the drone which are the fundamental angles only. Some papers even combined between different types of the drone as have been done in this thesis[60] as the authors combined between the horizontal and the extendable drone.

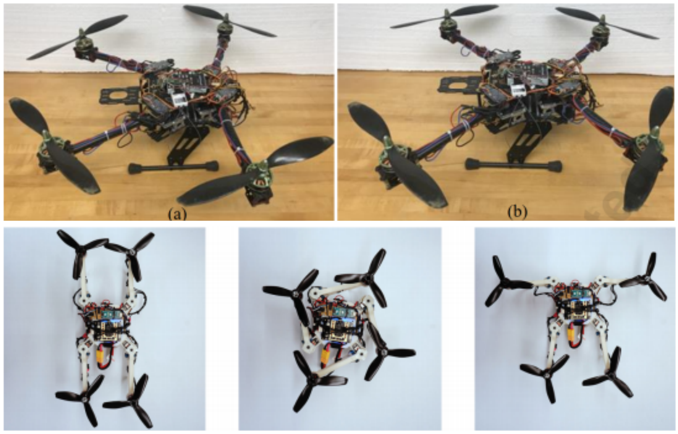

Figure 1.21: Different folding morphologies [61] up and down [38]

And by all of that, it is clear that the drones field is diverse and vast. But what is really the domain of application of the drones? And are the drones useful as the researches claim?

1.4 Applications of drones

Today drones are used in different sort of applications, environmental protection [27], power infrastructure monitoring [14], and urban planning and management [15]. In the

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[4] Linear Quadrator Regulator

thesis[73] exploited drones potentials in logistics industry, as it classified the several uses of drones in a warehouse. Where the drone has different applications such as Inventory Management, Intra-Logistics, Inspection and Surveillance.

Some researches explored the medical application of drones like it has been done in [74] where the authors classified the drone used in the medical field in three subdivisions. First medical surveillance in public health and that by the surveillance of disaster sites, detect health hazards such as radiation and epidemiology research, Fornace et al [23] managed to characterize the land changing and deforestation patterns in Malaysia using a drone.
[74] mentioned also Drones as Medical Transport Systems and Telemedicine describing it as "One of the most promising uses of drones" that gives remote diagnosis and treatment to patients who don't have access to a doctor or a clinic.
The authors of the review in [75] on the other hand covered the applications of drones in the mining industry, where drones where used in surface mining, underground mines, abandoned mine and even on rescue operations.

Due to the different applications of the drones, that can sometimes require a morphology adaptation with the environment, what will result different ways to control the drone so what ways were they used to control the transformable quadrors and the configurable drones?

1.5 Control of the transformable drones

The transformable quadrotor makes the controlling logic quit a hard task to do as stabilization and precision errors increase due to the variable structure and for that numerous control techniques have been suggested to command the transformable quadcopter both linear and non linear.
In previous works such as have proved possible to control a foldable quadrotor using linear control methods using the PID as did Zhao et al. [39] [40] in order to control the horizontal position of a transformable UAV. Oosedo et al [41], used a PID controller on a tilt rotor drone to command the attitude transition for pitch angles. PID was Also used to control the position and altitude on an extendable arms drone in [41] [42].
(LQR) and LQI[5] the other linear control methods that proved efficiency as have proved Barbaraci et al. [43] using LQR on a variable geometry arms quadcoptor as it angles between the arms variate with keeping a symmetrical structure. An adaptive LQR was discussed by Falanga et al. [44] to assure a stable hovering of the rotating arms quadcoptor .

Some previous works proved the possibility to control the quadrotor using linear control methods by linearizing the dynamics around an operating point, such as (DFL) the Dynamic Feedback Linearization in [45] presented by Raj and al in order to command the altitude of a reconfigurable UAV, as did Flores and a in [47] using Linearization by

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[5] Linear Quadrator Integral

Feedback to stabilize the flight of a transformable tail-sitter drone

In order to have better performances we lean toward using nonlinear controlling techniques that are considered as the general case in UAV flight dynamics.
Derrouaoui et al. [46], used backstepping as a new control strategy in order to to stabilize a foldable UAV, the result showed the efficiency of the control in condition of the respect of the rotating arms angles and the drone structure. Mu et al. [48] used Sliding Mode (SM) controller for the position control of a modular multirotor, as well as Inertial Measurement Unit (IMU) to estimate the configuration change.

1.6 Quadrotor modeling

In general, there are several models to describe the same system, this is due to the fact that real systems are affected by several internal parameters and their environments.For this reason finding an alternative simple models comes as a necessity.which only take into account the most contributing effects (contributors), see no effect), and other so-called complex models.

It is for this reason that we can find so-called simple models (which only take into account the most contributing effects (contributors), see no effect), and other so-called complex models (which take into account all the effects capable of being modeled and calculated).The different models are used according to the need, in general the simple models are used for the commands where the response must be fast and the error acceptable, a complex model would generate a very long computation time for a result which is not very different from that with a simple model since most of the added effects do not affect the system very much under operating conditions, however complex models are ideally used for studies of improving the performance of systems.

Models can be classified into two categories: modelization according to Euler-Lagrange and modelization according to Newton-Euler [77] :

1.6.1 modelization according to Euler-Lagrange

"Modélisation dynamique de bouabdellah et al . [38]"
In [32] and [21], lozano et al on his work "Modèlisation dynamique de lozano et al" used the aproch of Euler-Lagrange, in order to make the quadrotor model. His work was based on finding Lagrangien (L) and kinetic energy that self is composed of two terms: kinetic energy of translation and kinetic energy of rotation

Newtonian mechanics can be reformulated by Lagrange and Hamilton equations [76].

1.6.2 modelization according to Newton-Euler

From the previous mentioned models, the quadrotor modeling can be done according to it *"options"*

For example there is the quadrirotor model with flow deflector [76], the quadrotor model with twin rotor and cylindrical plate [76].

The previous examples concerned quadrotors which are physically different, however many of the improvements are made by equipping the quadrotors with more sensors and intelligence to achieve a certain degree of autonomy [77].

-Mechanical modeling: Geometric parameters, kinematic parameters, kinetic parameters.
-Electro-mechanical modeling of motors

Models may include the problems encountered by the quadrotor, such as the landing problems known to be the most delicate phase of piloting. One of his problems is *VRS*[6] which is the cause of several spitting from drones and helicopters.

1.7 Challenges and Contribution

One of the functional advantages of the drones is the effective gather of real time data in terms of cost. That basically initiated the rapid growth of drone use in many domains,from commercial and to industrial to even medical but in the presence of the vast use of the drones what are the challenges that slow it growth and development?

1.7.1 Challenges of drones

Despite the promising advantages that the drone represents and the accelerating maturation of it applications, it still faces several challenges that prevent the drones from reaching it full potential.Some of this challenges are the weather conditions that is considered as a serious issue that can lead to the failure of the drone.
Energy consumption is also an annoying issue, when hovering, wireless connection, data, and image processing all relay on the battery of the drone as an energy source, despite that some controls aim to optimise energy [78] but it still is challenging in the case of the drones. Several missions using the drone, had to pick some operations and cancel the other in order to keep the battery alive [75].
Confined and complex spaces, obstacles and limited hovering area, representing environment issues can be face in underground mines [75], these issues can lead to the crash of the drone and it definitive failure.

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[6] Vortex ring state

1.7.2 Contribution to knowledge

To make the drones more adapted to their environment, they need to be transformable in order to have more flexible maneuver through the obstacles.
So in this thesis we worked on the modeling of the transformable quadcopters in order to study the adaptation of the drone with it environment, with the comparison of the numerical and the mathematical models using a PID control.

1.8 Conclusion

This chapter covered some dates in the history of drones that we think were the boost toward what the drones achieved today. It also covered UAV classification and some different configurable prototypes that we believe can shape the future of drones, but that does not mean it covered it all but what we could reach to from the letrature as the UAV field becomes wider everyday. And after having different studies on configurable drones mentioned in this chapter we will have our own work about this field in the next chapters.

Chapter 2

Foldable quadcopter model

Contents

2.1 Introduction

The foldable quadrotor uses different phenomena that are necessary to solve the challenges and problems due to the mechanical complicity of the quadrotor such as Euler angles and NEWTON motion law. So this chapter will explain how these laws will be introduced in the phenomena acting on the foldable quadrotor.

2.2 NEWTON motion law in the quadcopter

In order to lift any object up of the ground, the vertical sum of the forces should be positive by the second law of NEWTON.

$$F_g \leq \sum F \Longrightarrow mg = F_1 + F_2 + F_3 + F_4 \tag{2.2.1}$$

In order for the UAV to fly and by the second law of motion the sum of the forces applied on the quad-rotor must be positive in other words the forces pushing up must be superior than the forces pulling down.
So for that we need one propeller to create us a lifting force that we thrust bigger than the gravity force. Actually two opposite rotors are enough to make the Arial vehicle fly as long it keeps the body does not rotate around y or x axes in other words the forces applied on x or y axe cancel each other. But in that case the two rotors will generate a torque opposite to their rotation direction that will cause the drone to rotate around its center.
So to avoid that we are brought to add two other rotors to cancel the torque generated as showed in the figure 2.1.

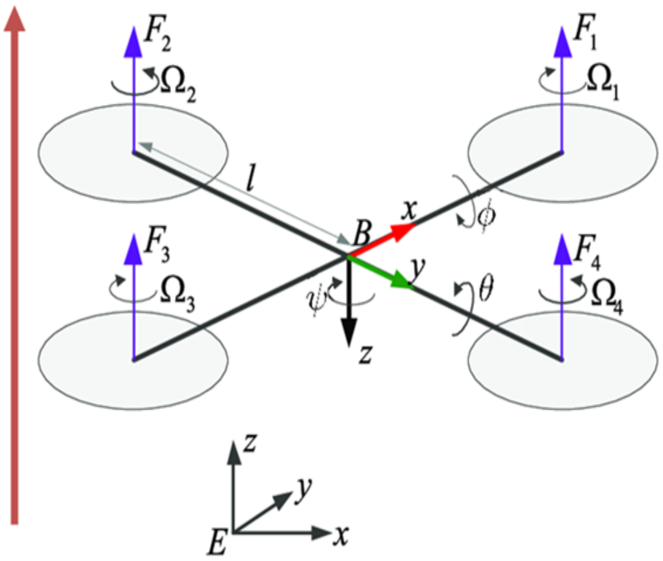

Figure 2.1: Quadcopter illustration and the forces behaving on it

The quadcopter has four main manoeuvres yaw, pitch, roll and hover that make it move into any unlimited space. quadrotors usually consider their system origin confounded with the gravity center or in an off set as in the figure 2.1 that represtes a 3 dimensional Cartesian system (x, y, z) with the origin E.

1- We covered the take off scenario in order to fly the drone up, now in order to maintain that flying altitude or what we call hovering we use the second law of motion one more time where the sum of the forces is equal to zero or in other words the weight force equal to the lift force.

$$\sum F = 0 \Longrightarrow mg = F_1 + F_2 + F_3 + F_4 \tag{2.2.2}$$

2-Yaw is the action that makes the whole quadcopter body spins around the z axe that passes by its GC[1]. And that is caused the two opposite rotors generate more force than the other two rotors, just like the case of two rotors quadcopter.
The quad-rotor yawing clockwise : $F_2 + F_4 \geq F_1 + F_3$
The quad-rotor yawing counter clockwise : $F_2 + F_4 \leq F_1 + F_3$

3- Pitch the quad tilt forward or backward caused by the generated positive or negative angle between the y, x plane and the quad body and that by having the front rotors generating more force than the back ones or the opposite way.
- The quad-rotor pitching backwards : $F_1 + F_2 \geq F4 + F3$
- The quad-rotor pitching forwards : $F_1 + F_2 \leq F_4 + F_3$

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[1] Gravity Center

4- Roll tilt the copter left or right caused by the generated positive or negative angle between the y, z plane and the quad body and that by having the right rotors generating more force than the left ones or vice versa. • The quad-rotor rolling to the left : $F_1 + F_4 \geq F_2 + F_3$

• The quad-rotor rolling to the right : $F_1 + F_4 \leq F_2 + F_3$

In all the previous cases the motion law is respected $\sum F = 0$

In the next figure 2.2 we considered an X configuration quadcopter but in addition to the that we can have a Plus configuration quad-rotor as the next figure illustrates.

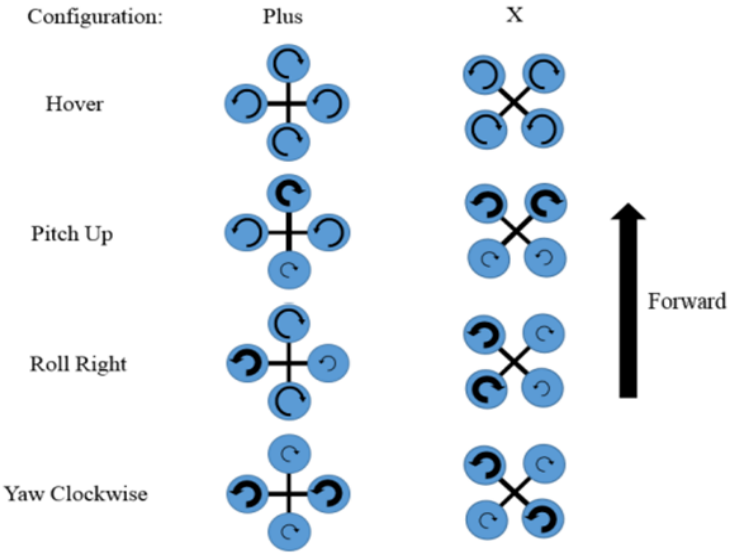


Figure 2.2: X and PLUS configuration

2.3 Dynamic of the foldable quadcopter

Just like the standard quadrotor, each opposite pairs has the same rotation direction. The second and the fourth rotor turn clockwise and for first and the third they turn counterclockwise in order to have the six degrees of freedom motions $(\psi, \phi, \theta, x, y, z)$.
In addition the folding the arms of the quadrotor changes the morphologies as shown in the figure 2.3. Using a servomotor that attaches each arm to the body what makes an over actuated system, what makes system a highly coupled with a higher number of operable control than the controlled parameters .

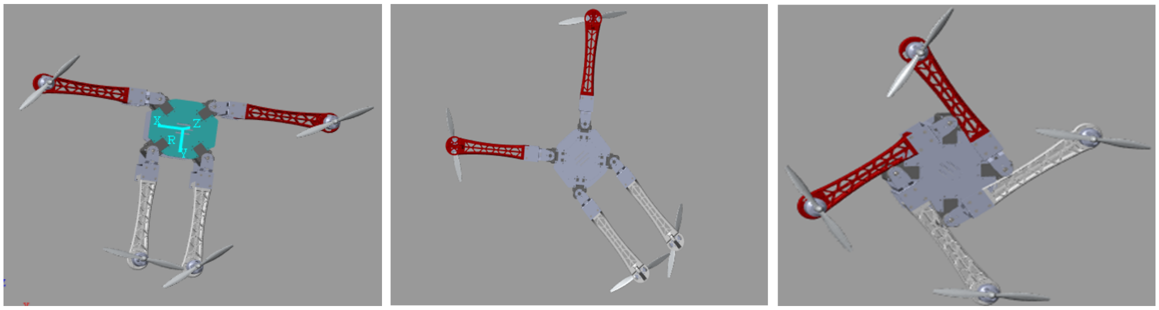


Figure 2.3: Different morphologies that can be performed by a foldable quadrotr(T,Y,O) respectively

2.3.1 Hypotheses on the foldable quadrotor model

In order to make a mathematical model of a foldable quadrotor, it is important to make some suppositions and some hypotheses that helps make an adequate model, these suppositions are defined as follow:

- The quadrotor parts are assumed to be rigid.
- The propellers are assumed to be rigid in order to be able to neglect the effect of deformation during rotation.
- The lift and drag forces are assumed to be proportional to the square of the rotational speed of the rotors.
- The lift and drag forces are assumed to be proportional to the square of the rotational speed of the rotors.

The foldable quadcopter as showed in the figure 2.4 is composed of a central body m_0 in which the four arms of the mass $m_{2,i}$, are attached to each via a servomotors $m_{1,i}$ and supporting the rotors of the mass m_2 numbered from 1 to 4, each matching the number of the arm supporting it.
Four points are defined on each arm, each point represents a Cartesian coordinate system origin.

$G_{1,i}$ representing the folding arm point, $G_{2,i}$ representing the center of the arm and $G_{3,i}$ representing the center of the rotor, for $i = [1;4]$. In addition to the point defining the central body or the geometric center O and the point that represents the gravity center $G_{0,0}$.

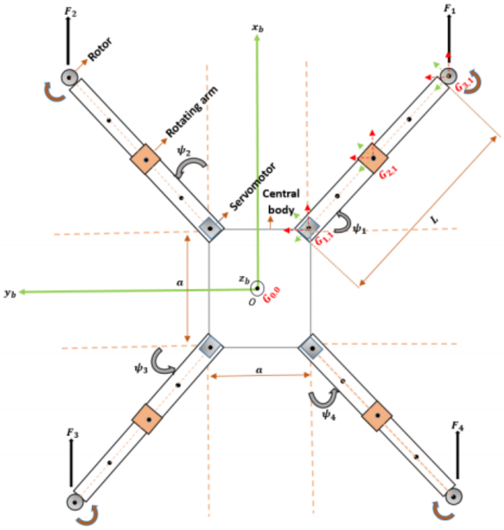


Figure 2.4: Landmarks on the foldable quadrotor

2.3.2 Euler angles

Euler angles are the mathematical tool introduced by Leonhard Euler, representing three angles that permit the angular transformation of Cartesian coordinate system (x, y, z), which is demonstrated in the figure 2.5 that represents:

- $\phi \in \,]-\pi, \pi]$ is the angle generated when the system rotates around the axe x.
- $\psi \in \,]-\pi, \pi]$ is the angle generated when the system rotates around the axe z.
- $\theta \in \left]-\frac{\pi}{2}, \frac{\pi}{2}\right[$ is the angle generated when the system rotates around the axe y.

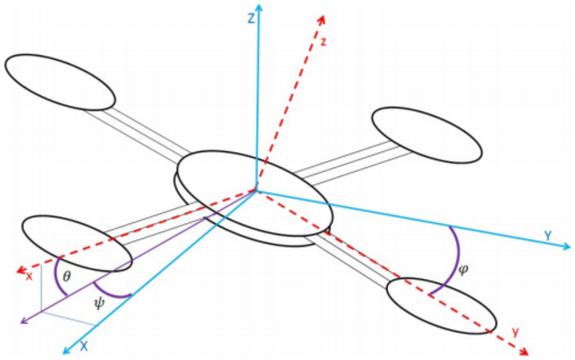


Figure 2.5: Euler angles

We consider the rotation around the axes x, y, z that generates the elementary angles ϕ, θ, ψ respectively. These angles represent the three elementary rotations that generates the next rotation matrices:

$$\mathrm{R_x} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c(\phi) & -s(\phi) \\ 0 & s(\phi) & c(\phi) \end{bmatrix} \tag{2.3.1}$$

$$\mathrm{R_y} = \begin{bmatrix} c(\theta) & 0 & s(\theta) \\ 0 & 1 & 0 \\ -s(\theta) & 0 & c(\theta) \end{bmatrix} \tag{2.3.2}$$

$$\mathrm{R_z} = \begin{bmatrix} c(\psi) & -s(\psi) & 0 \\ s(\psi) & c(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2.3.3}$$

The elementary rotation matrices can be combined to achieve any point in the space covered by the Cartesian system using vector multiplication, what result the following matrix:

$$\mathrm{R_{xyz}} = \mathrm{R_x R_y R_z} = \begin{bmatrix} c(\theta)c(\psi) & s(\phi)s(\theta)c(\psi) - c(\phi)s(\psi) & c(\phi)s(\theta)c(\psi) + s(\phi)s(\psi) \\ c(\theta)s(\psi) & s(\phi)s(\theta)s(\psi) + c(\phi)c(\psi) & c(\phi)s(\theta)s(\psi) - s(\phi)c(\psi) \\ -s(\theta) & s(\phi)c(\theta) & c(\phi)c(\theta) \end{bmatrix} \tag{2.3.4}$$

2.4 Gravity Center and Inertia

With the morphlogy adjusments that the fodebale quadrotor makes, the quadrotor changes it gravity center due to the the individual rotation of each arm, what we need to take on consideration in our numerical model.
We consider:

a : the acceleration of the quadrotor.
ξ : the quadrotor position with respect to the inertial frame.
m : the quadrotor total body mass.
ω : the angular velocity.
$J_s/O(\psi_i(t))$: the inertia of the system during the folding process due to the variation of the rotation angle $\psi_i(t)$ of the arms brought to to the geometric center O.
F_t : the resultant of four generated forces by the rotors:
with : F_i=K_l ω_i^2 : the force generated by each rotor.
and K_l represents the lift coefficient of each rotor witch is the same for every rotor.
ω_i angular velocity of each rotor i = $1, 2, 3, 4$.
what brings us to: F_t=$R[0\ 0 \sum_{i=1}^{4} F_i]$
F_d : the resultant of the drag forces along (X, Y, Z) axes:

$$F_d = diag(-K_{dx}K_{dy}K_{dz})\xi' \tag{2.4.1}$$

with K_{dx}, K_{dy}, K_{dz} are the translation drag coefficients.
For the gravity g, F_g represents the force gravity:

$$F_g = [0\;0\;-mg]^T \tag{2.4.2}$$

The moment caused by the thrust and drag forces M_f is expressed as follows:

$$M_f = \begin{pmatrix} M_x \\ M_y \\ M_z \end{pmatrix} \tag{2.4.3}$$

For aerodynamic friction coefficients K_{ax} K_{ay} K_{az} the resultant of aerodynamic friction torques M_a is expressed as follows:
The resultant of aerodynamic friction torques

$$M_a = diag(K_{ax}\;K_{ay}\;K_{az})\omega^2 \tag{2.4.4}$$

Due to the gyroscopic effect and for J_r is the rotor inertia the resultant of torques M_{gy} is defined as fellow:

$$M_{gy} = \sum_{i=1}^{4} \omega * J_r[0\;0(-1)^{i+1}w_i] \tag{2.4.5}$$

Using all the above, and using Newton-Euler formalism that expresses the relation between the external forces and the velocities and the moments applied on the GC illustrated as follow:

$$\sigma(s,i) = \begin{cases} m\xi'' = F_d + F_t + F_g \\ J_s/O(\psi_i(t))\omega = -\omega * J_s/O(\psi_i(t))\omega + M_f - M_a - M_{gy} \end{cases} \tag{2.4.6}$$

2.4.1 Calculation of the Center of Gravity

Due to the physical changes of the quad-rotor, that includes non symmetrical configurations and due to the variation of the GC, it is important to make a general formula that defines every configuration of the GC that is expressed as follow:

so for:

$$\overrightarrow{OG} = \begin{pmatrix} \mathrm{x_G} \\ \mathrm{y_G} \\ \mathrm{z_G} \end{pmatrix} \tag{2.4.7}$$

et

$$\overrightarrow{OG_0} = \begin{pmatrix} \mathrm{x_0} \\ \mathrm{y_0} \\ \mathrm{z_0} \end{pmatrix} \tag{2.4.8}$$

$$\overrightarrow{OG_{1,i}} = \begin{pmatrix} \mathrm{x_{1,i}} \\ \mathrm{y_{1,i}} \\ \mathrm{z_{1,i}} \end{pmatrix} \tag{2.4.9}$$

$$\overrightarrow{OG_{2,i}} = \begin{pmatrix} \mathrm{x_{2,i}} \\ \mathrm{y_{2,i}} \\ \mathrm{z_{2,i}} \end{pmatrix} \tag{2.4.10}$$

$$\overrightarrow{OG_{3,i}} = \begin{pmatrix} \mathrm{x_{3,i}} \\ \mathrm{y_{3,i}} \\ \mathrm{z_{3,i}} \end{pmatrix} \tag{2.4.11}$$

O : The origin of the quadcopter.

$\overrightarrow{OG} \in R^{3*1}$: The offset between the geometric center of the system and the global center of gravity.

$\overrightarrow{OG_{0,i}} \in R^{3*1}$:The offset between the globade variable body center and the body GC.

$\overrightarrow{OG_{1,i}} \in R^{3*1}$: The vector of the center of gravity of the servomotors.

$\overrightarrow{OG_{2,i}} \in R^{3*1}$: The vector of the center of gravity of the rotating arms.

$\overrightarrow{OG_{3,i}} \in R^{3*1}$: The vector of GC of the rotors.

$$\overrightarrow{OG} = \frac{\sum_{i=1}^{4}\sum_{j=1}^{3} \mathrm{m_{j,i}}\overrightarrow{OG_{ji}}}{m_0 + \sum_{i=1}^{4}\sum_{j=1}^{3} \mathrm{m_{j,i}}} \tag{2.4.12}$$

2.4.2 Calculation of the Inertia

Due to the morphology variation of the quadrotor, makes the Inertia calculation of the structure tend to be complex, so it is necessary to take the following approximations: The central body is approximated to a cube.
Using the parallel axis theorem, the calculation of the inertia matrix is given as follow: Inertia matrix of the central body:

$$j_{(0)/O} = m_0 \; diag\left(\frac{a^2 + h^2{}_0}{12}, \frac{a^2 + {h_0}^2}{12}, \frac{2a^2}{12}\right) \tag{2.4.13}$$

Inertia matrix of the servomotors:

$$J_{(1,i)/O} = J_{G1,i} + \begin{pmatrix} {y_{1,i}}^2 & -x_{1,i}y_{1,i} & 0 \\ -x_{1,i}y_{1,i} & -{x_{1,i}}^2 & 0 \\ 0 & 0 & {x_{1,i}}^2 + {y_{1,i}}^2 \end{pmatrix} \tag{2.4.14}$$

where

$$j_{G_{1,i}} = m_0 \; diag\left(\frac{L^2{}_1 + h^2{}_1}{12}, \frac{w^2{}_1 + h^2{}_1}{12}, \frac{L^2{}_1 + w^2{}_1}{12}\right) \tag{2.4.15}$$

Inertia matrix of the rotating arms:

$$J_{(2,i)/O_{rot}} = R_z(\psi_i(t)).J_{(2,i)/O}.R_z(\psi(t)_i)^2 \tag{2.4.16}$$

where

$$J_{(2,i)/O} = J_{G_{2,i}} + m_{(2,i)} \begin{pmatrix} {y_{2,i}}^2 & -x_{2,i}y_{2,i} & 0 \\ -x_{2,i}y_{2,i} & -{x_{2,i}}^2 & 0 \\ 0 & 0 & {x_{2,i}}^2 + {y_{2,i}}^2 \end{pmatrix} \tag{2.4.17}$$

$$J_{G_{2,i}} = m_0 \; diag\left(\frac{L^2{}_2 + h^2{}_2}{12}, \frac{w^2{}_2 + h^2{}_2}{12}, \frac{L^2{}_2 + w^2{}_2}{12} \right) \tag{2.4.18}$$

Inertia matrix of the rotors:

$$J_{(3,i)/O_{rot}} = R_z(\psi_i(t)).J_{(3,i)/O}.R_z(\psi(t)_i)^2 \tag{2.4.19}$$

$$J_{(3,i)/O} = J_{G_{3,i}} + m_{(2,i)} \begin{bmatrix} {y_{3,i}}^2 & -x_{3,i}y_{3,i} & 0 \\ -x_{3,i}y_{3,i} & -{x_{3,i}}^2 & 0 \\ 0 & 0 & {x_{3,i}}^2 + {y_{3,i}}^2 \end{bmatrix} \tag{2.4.20}$$

$$J_{G_{3,i}} = m_{3,i} \; diag\left(\frac{r^2}{4} + \frac{h^2{}_3}{12}, \frac{r^2}{4} + \frac{h^2{}_3}{12}, \frac{r^2}{2} \right) \tag{2.4.21}$$

$$J_{(3,i)/O}\psi_i(t)) = J_{(0)/O} + \sum_{i=1}^{4} J_{(1,i)/O_{rot}} + \sum_{i=1}^{4} J_{(2,i)/O_{rot}} + \sum_{i=1}^{4} + J_{(3,i)/O_{rot}} \tag{2.4.22}$$

Allocation Matrix
for

$$M_{x,y} = \sum_{i=1}^{4} \overrightarrow{GG}_{(3,i)} \wedge F_{i,\vec{e}_z} \tag{2.4.23}$$

and

$$A = \begin{bmatrix} K_l & K_l(y_{3,1} - y_G) & K_l(-x_{3,1} - x_G) & K_d \\ K_l & K_l(y_{3,2} - y_G) & K_l(-x_{3,2} - x_G) & -K_d \\ K_l & K_l(y_{3,3} - y_G) & K_l(-x_{3,3} - x_G) & K_d \\ K_l & K_l(y_{3,4} - y_G) & K_l(-x_{3,4} - x_G) & -K_d \end{bmatrix} \tag{2.4.24}$$

and

$$\sigma(s,i) = \begin{cases} x_{3,1} = \dfrac{a}{2} + (L + r)\sin\psi_1(t) \\ x_{3,2} = \dfrac{a}{2} + (L + r)\cos\psi_2(t) \\ x_{3,3} = \dfrac{a}{2} + (L + r)\sin\psi_3(t) \\ x_{3,4} = \dfrac{a}{2} + (L + r)\cos\psi_4(t) \\ y_{3,1} = \dfrac{a}{2} + (L + r)\cos\psi_1(t) \\ y_{3,2} = \dfrac{a}{2} + (L + r)\sin\psi_2(t) \\ y_{3,3} = \dfrac{a}{2} + (L + r)\cos\psi_3(t) \\ y_{3,4} = \dfrac{a}{2} + (L + r)\sin\psi_4(t) \end{cases} \tag{2.4.25}$$

we get

$$\begin{pmatrix} M_T \\ M_x \\ M_y \\ M_z \end{pmatrix} = A \begin{pmatrix} {\omega_1}^2 \\ {\omega_2}^2 \\ {\omega_3}^2 \\ {\omega_4}^2 \end{pmatrix} \tag{2.4.26}$$

2.5 Conclusion

The hypotheses and the assumptions make the mathematical model little different than the real one, so would these differences misguide the results? that what we will see in the next chapters by comparing between the mathematical and real model results.

Chapter 3

Conception of numerical model of the foldabe quadrotor

Contents

3.1 Introduction

Computer simulations plays an important role in the science improvement, as it allows to explore different horizons and testing hypotheses with no limitation applied caused by the physical conditions. Matlab is an important platform that supports different systems representations, consequently the simulations needed.
A numerical model supported by simmechanics that represents one of Simulink tools, is chosen to make the foldable quadrotor experiments as well as it control. The reason behind this choice is that the numerical model is close to physical real experiment.
This chapter will explore different steps taken, in order to make the numerical model and it control.

3.2 Used software

SolidWorks

SolidWorks is a solid modeling computer-aided design (CAD) that allows the 2D and the 3D design it is also a computer-aided engineering (CAE) computer program it is one of the industry's leading 3D CAD tools published by Dassault Systèmes [67].

MATLAB

MATLAB is a programming platform developed by MathWorks, designed to analyze and design systems and products usually used by engineers and scientists .MATLAB uses a matrix-based language called MATLAB language allowing the most natural expression of computational mathematics such as simulink .

SIMULINK

SIMULINK is a functional diagram environment for multi-domain simulation and the Model-Based Design approach. It supports system-level design and simulation, automatic code generation, and continuous testing and verification of on-board systems [72].

SIMULINK offers a graphics editor, a customizable set of block libraries and solvers for modeling and simulating dynamic systems. It is integrated with MATLAB, which allows you to incorporate MATLAB algorithms into models and export simulation results to MATLAB to supplement analyzes [72].

3.3 Conception of the 3D model

The numerical model needs a 3D design or representation of the foldable quadrotor, that represents an identical in shape as in size of the real quadcopter, and that in order to get reliable results.
The foldable quadrotor3D model is made using solid works as a cad software, the pieces that makes the design are downloaded from GrabCAD community and used to make the assembly.
These pieces are defined in the following section as well as their use.

3.3.1 Quadrotor CAD parts

BASE

First the upper and bottom piece of the central body (the quadrotor base) represented in the following figure 3.1 on which the rest of the quadrotor pieces are based, these two pieces are modified to have the servomotor fit in order to allow the arms rotation.

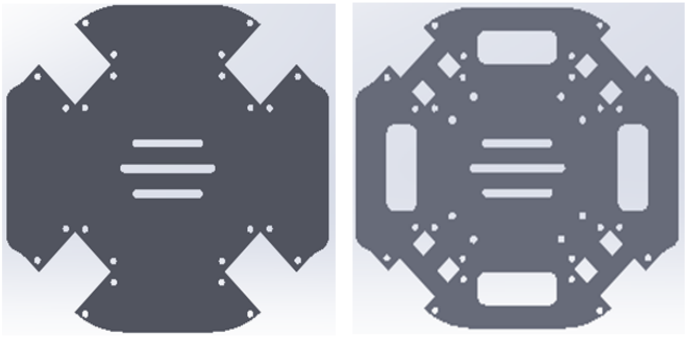


Figure 3.1: Right represents the upper piece of the central body, on the left the bottom piece of the base

AX-12 servomotor

Picking the right servomotor can be critical as it have to satisfy some physical constraint such as speed and torque.
Dynamixel AX-12A is used in this thesis as part of the foldeable quadrotor model, as it fits it physical conditions.

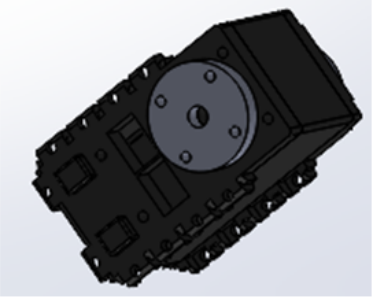


Figure 3.2: AX12a servomotor

Dynamixel AX-12A is a 54.6g Cored motor with 32mm * 50mm * 40mm in width, height and depth respectively in addition the servo has a delay time that in the range os 0 to2 [μsec] [65], extra information are listed in the table below that justifies the choice of such a servomotor.

Stall Torque [N.m]	1.50
Stall Current [A]	1.5
No Load Speed [rpm]	59.0
No Load Current [A]	0.14
Feedback	Position, Temperature, Load, Input Voltage
Operating Mode	Joint Mode 300 [deg] Angle-Wheel Mode Endless turn

Table 3.1: Parameters of AX12a rotor [65]

Joints

There are two types of joints used to link the arms to the main core, the first comes with the AX12a servo motor that fits right on it like the figure 3.4 shows, the second is designed joint that links the previous joint to the arm figure 3.4.

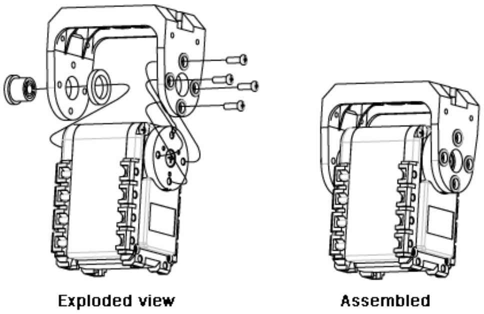


Figure 3.3: AX12 servomotor and the joint supporting it

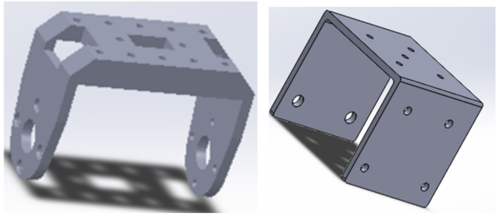


Figure 3.4: Two joints linking the arms to the body

Arms

The used arms are 21cm long, that support the $rotor - proppeler$ assembly linked to the AX12a servomotor that allows it to rotate 360 degrees on Solidworks, it is designed in two colors to distinguish the front pairs from the back pairs or the left ones from the right ones.

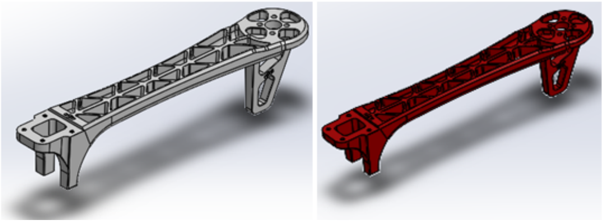


Figure 3.5: The arms holding the rotors

Rotor and propeller

For the rotors a Brushless A2212 / 6T 2200KV DC (direct courant) Motor was used, it wieghts 49g, charging curent is 21.5A,Internal resistance of 90mΩ, power of 239 W that makes the motor lift up to 732g and almost 2.928kg the four motors combined what makes it more than enough for the 1.6 kg quadrotor used in this project.
The A2212 / 6T 2200KV DC Motor uses 8x4.5 inch 8045/8045R Propellers they are plastic propellers with two thin blades making the total length of 204mm with the weight of $20mg$.

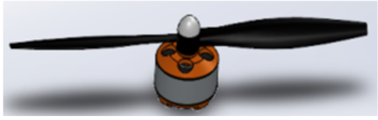


Figure 3.6: A2212/6T rotor and it propeller

During the assembly it is important to join the parts the same way every time, as the parts are multiplied in four or more (the case of the screw) because every part will be transformed to functional blocs on simmechanics, the virtual links between the parts will also be transformed into joint blocs, so being organised on solidworks will lead into a comprehensive organised numerical model.

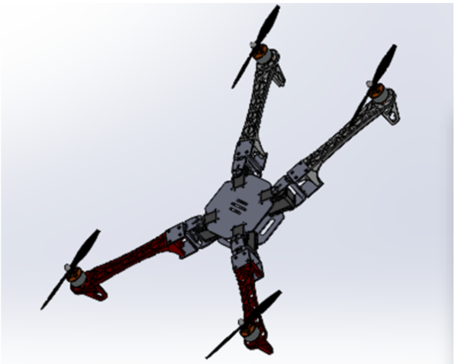


Figure 3.7: Final assembly of the quadrotor on Solidworks

3.3.2 Solid works to Simscape

First thing to do is to download a solidworks plug in from mathworks that allows to connect the two pieces of software (solidworks and matlab). On mathworks products page and following the Simmechanics multibody link that has all the download links. Pultiple download links are found on this page depending on the version of matlab and the type of computer used. It is essential to put the downloaded files on a clear folder path. On the editor window on matlab and using the code *install_addon* ”the name of the zip file downloaded”. On the same window we use the code "regmatlabserver" in order to register matlab as an automation server what allows the connection of the two softwares. Finally, in order to enable the simscape multibody link this code is used *”smlink_linksw"* and by that the connection between solidworks and matlab is done. And all is left to do is port the pieces designed on solidworks toward matlab using simmechanics plug installed before and that by following tools $\backslash simmechanics$ link $\backslash export$ $\backslash simmechanics$ what will allows to save the file as a .XML file, that will be loaded to simmechanics. Now, on the editor window of matlab using the code *"sm_import"* the name of the file.xml” that will make a simmechanics model from it.

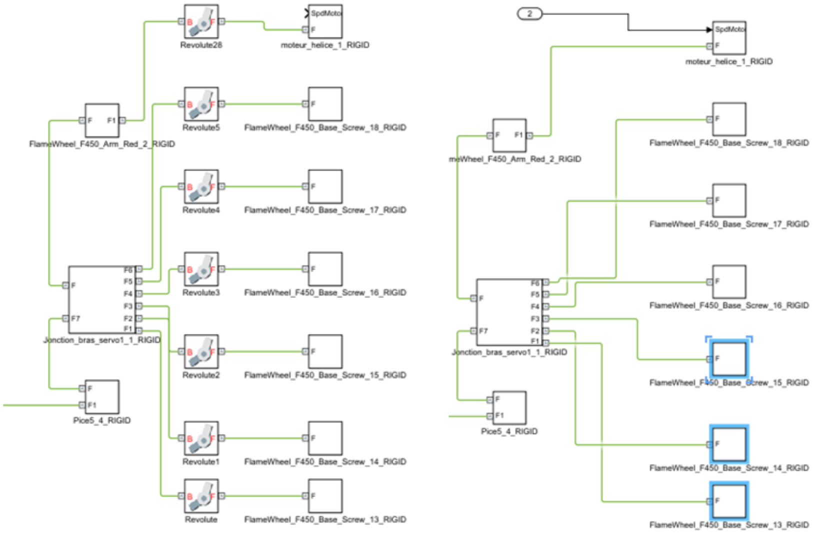


Figure 3.8: Quadcopter model on simulink obtained from SolidWorks before and after simplification

3.4 Numerical model

Once the assembly is done this 3D model is transferred to simulink on MATLAB Once the numerical model is loaded some changes need to be done such as deleting some blocs or adding some, these blocs are mainly the joints to make it either simpler or more efficient in the case of deleting and adding respectively [71].

In order to control the quadrotor, a control model made by Khanh Dang that goes under"Simulate Quadrotor in Simulink with SimMechanics" [71] on math works that it self was inspired by Leonardo Araujo's model. this controlling model contain four main subsystems as shown in the next figure 3.9. The subsystems will be described later on but first the blocs making these subsystems are defined.

3.4.1 Simmechanics bolcs used to make the numerical model

Joints

There are several joints used in the numerical model , they are use to represent the articulations of the the quadcopter. Some used to have the feedback of the parameters of the quadcopter and some are used to express the existence of an articulation on the quadcopter numerical model. The types of joints used will be explored next.

Revolute joint Represents a joint acting between two frames. This joint has one rotational degree of freedom represented by one revolute primitive. Used the four pivoting points that link the arms to the central body of the quadcopter and on the rotating points

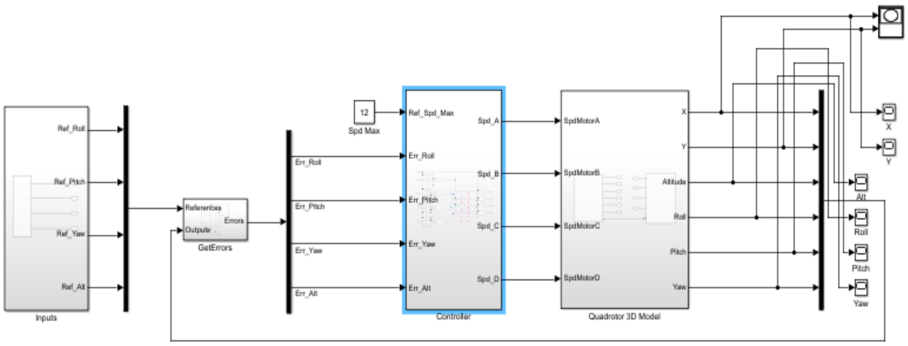


Figure 3.9: Numerical model of the foldable quadrotor

of the propellers to express articulations, in addition, it is used to have a feedback on the yaw, pitch and roll, every one at a time.
The joint constrains the origins of the two frames to be coincident and the z-axes of the base and follower frames to be coincident, while the follower x-axis and y-axis can rotate around the z-axis.

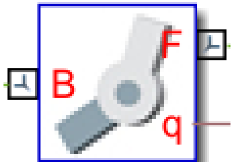


Figure 3.10: Revolute joint

Rectangular joint Represents a rectangular joint between two frames. This joint has two translational degrees of freedom represented by two prismatic primitives along a set of two mutually orthogonal axes. Used to have the feedback of the position of the quadcopter on both x and y axes. This joint constrains the z-axes of the base and follower frames to be aligned and prohibits relative translation along that axis.

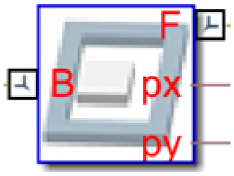


Figure 3.11: Rectangular joint

Prismatic joint Represents a prismatic joint between two frames. This joint has one translational degree of freedom represented by one prismatic primitive. Used to have a feedback of the altitude.The joint constrains the follower origin to translate along the base z-axis, while the base and follower axes remain aligned.

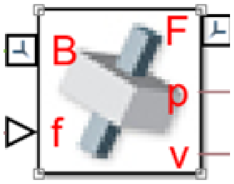


Figure 3.12: Prismatic joint

Frames

Reference frame

Defines a frame to which other frames in a network can be referenced or to which blocks can be attached. Reference frames are not required, but serve as a modeling and design convenience.

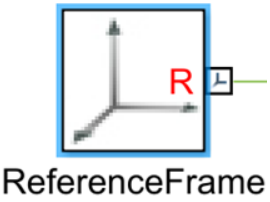


Figure 3.13: Reference frame

Word frame Provides access to the world or ground frame, a unique motionless, orthogonal, right-handed coordinate frame predefined in any mechanical model. World frame is the ground of all frame networks in a mechanical model.

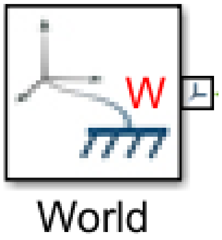


Figure 3.14: World frame

Converts

Physical to Simulink Signal Convert

Converts the input Physical Signal to a unitless Simulink output signal.

The unit expression in 'Output signal unit' parameter must match or be commensurate with the unit of the Physical Signal and determines the conversion from the Physical Signal to the unitless Simulink output signal.

Simulink to Physical Signal Convert

Converts the unitless Simulink input signal to a Physical Signal.

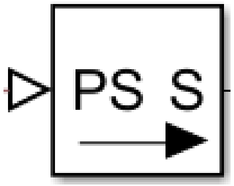


Figure 3.15: Physical to Simulink Convert

The unit expression in 'Input signal unit' parameter is associated with the unitless Simulink input signal and determines the unit assigned to the Physical Signal.

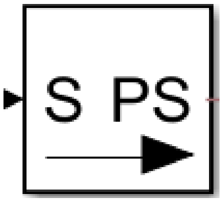


Figure 3.16: Simulink to Physical Convert

Addtional used blocs

External force and torque Applies an external force and torque at the attached frame. The force and torque are specified by the physical signal inputs. It is used to represent the force generated by the rotors.

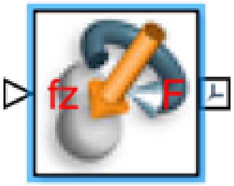


Figure 3.17: External force and torque

Transformer of references Defines a fixed 3D rigid transformation between two frames. Two components independently specify the translational and rotational parts of the transformation. Different translations and rotations can be freely combined.

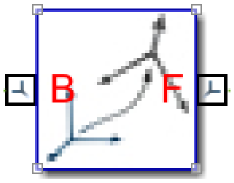


Figure 3.18: Transformer of references

Mechanism Sets mechanical and simulation parameters that apply to an entire machine, the target machine to which the block is connected. In the Properties section below, you can specify uniform gravity for the entire mechanism and also set the linearization delta. The linearization delta specifies the perturbation value that is used to compute numerical partial derivatives for linearization.

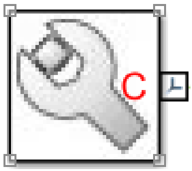


Figure 3.19: Mechanism bloc

3.4.2 References subsystem

It contains a signal generator block that can generates different signals at the same time with the ability to define the frequency and amplitude for each one.

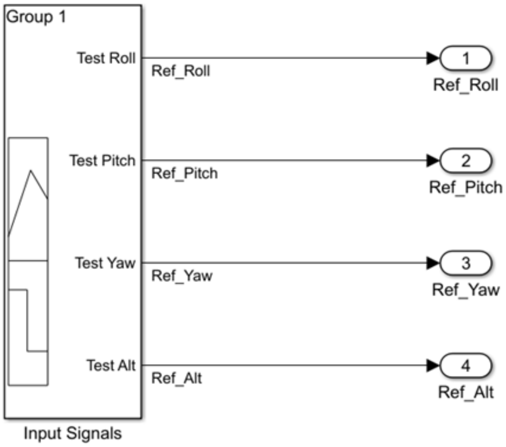


Figure 3.20: Bloc representing the inputs

To make the model more accurate, a different different inputs needs to be commanded which are the X and Y to observe the trajectories made by the quadrotor that is why an other bloc was added from the model of Mohamed Abdelkader Zahana [70] this bloc is responsible of converting the x and y inputs into pitch and roll angles.

3.4.3 Error subsystem

It basically built out of four comparators that makes the difference between the reference value of the altitude, Roll, Pitch and Yaw and their measured value what results the error that will be used in the next bloc.

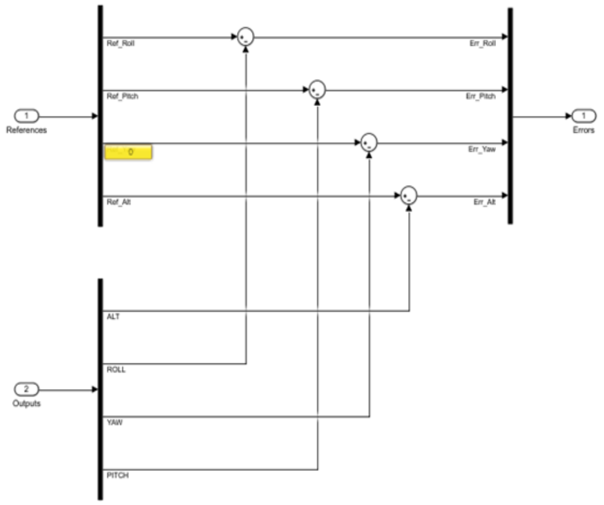


Figure 3.21: Bloc calculating the error between the inputs and outputs

3.4.4 Controller subsystem

It can be divided into three main parts :
- The regulation: It contains four PID controllers which all have the errors calculated in the previous bloc each is responsible of the regulation one of the parameter (yaw, roll, pitch and altitude).
- Mixing matrix: it represents a cabled mixing matrix that combines three parameters (altitude, pitch, roll or yaw)
- And the speed outputs: each rotor speed is obtained out of a mixing three parameters, each rotor has a different parameter combination; this combination is filtered before reaching the rotor.

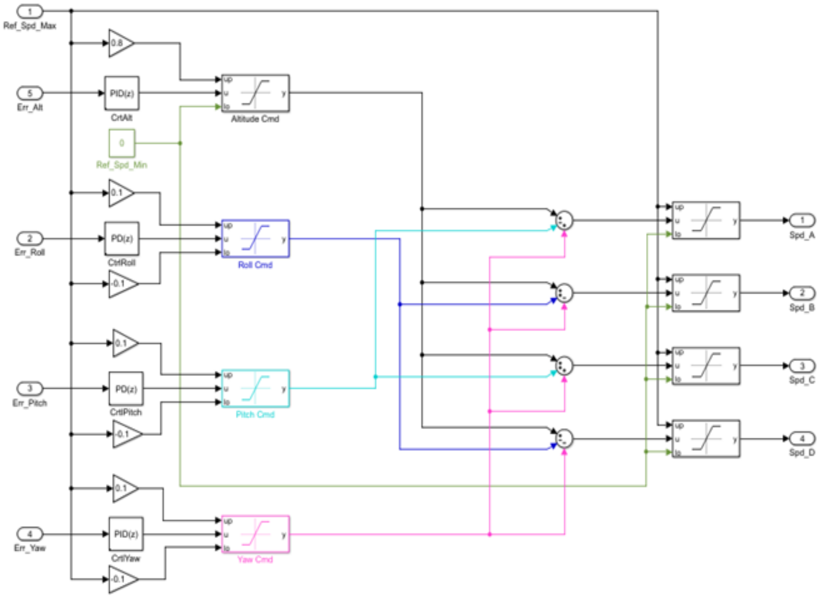
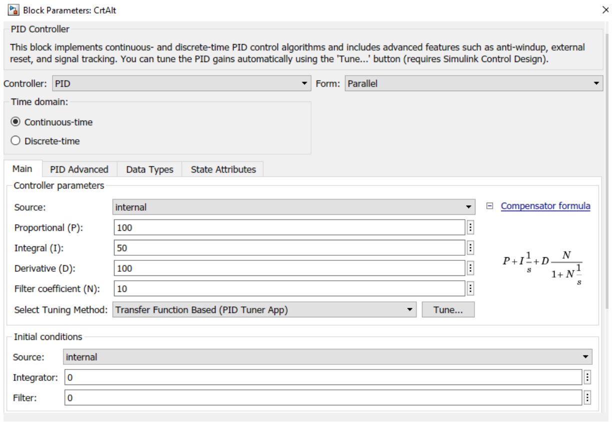


Figure 3.22: Bloc of controls

PID bloc

This bloc is responsible of the command and the control of the Quadcopter as it generates the necessary amount of speed needed to hover, pitch, yaw or roll based on the feedback values of the pitch, roll, yaw and altitude. This part of the model is mainly divided into four parts:
• The inputs: they contain four different inputs Altitude error, Roll error, the pitch error and the yaw error that represent the output of the Geterr bloc, each supports a data signal based on which the control signal is generated.
• The corrector: each signal is treated by a different PID controller that contain distinguished gains to compensate the error and cancel it figure 3.23, every PID controller is followed by a saturation in order to . It is used to cut the peaks signal in order to avoid the unsteady state and breaking the feedback loop in consequence.


Block Parameters: CrtAlt

PID Controller

This block implements continuous- and discrete-time PID control algorithms and includes advanced features such as anti-windup, external reset, and signal tracking. You can tune the PID gains automatically using the 'Tune...' button (requires Simulink Control Design).

Controller: PID
Form: Parallel

Time domain:
● Continuous-time
○ Discrete-time

Controller parameters

Source: internal
Proportional (P): 100
Integral (I): 50
Derivative (D): 100
Filter coefficient (N): 10
Select Tuning Method: Transfer Function Based (PID Tuner App)

$$P+I\frac{1}{s}+D\frac{N}{1+N\frac{1}{s}}$$

Initial conditions

Source: internal
Integrator: 0
Filter: 0

Figure 3.23: PID Bloc

As our system is a non linear system it is not obvious to get the right gains of the PID at the first try because modifying the PID gains of one action affects the other actions as in non linear systems has multiple maximum and minimums that can misguide the regulation into a minimum or a maximum that is not explicitly the optimal. This part contains also one integrator on the pitch command line that is used to reduce the static error.

- Mixing matrix : this part of the bloc contains the mixing vector implemented for each rotor speed that combines the values of the altitude, roll, pitch and yaw appropriately to every rotors in order to make the quadrotor hover, tilt and follow the trajectories set.

The four mixing vectors form a mixing matrix of four lines and three columns that changes with every configuration.

Actuator saturation bloc

All the actuators have physical limitations and due to that, the control variable may reach the limits of the actuators.
In that case the feedback is broken, and the system functions in an open loop, because the actuator is proceeding on limits that are independent from the process output. If the integrator action is used it will keep integrating the error until it reaches a very great value of the integrator output as a result. And that is called Windup.
Anti- Windup is used to avoid such scenarios as it allows us to limit the amplitude length as well as it period in case of the sinusoidal signal as the next figure 3.24 demonstrate.

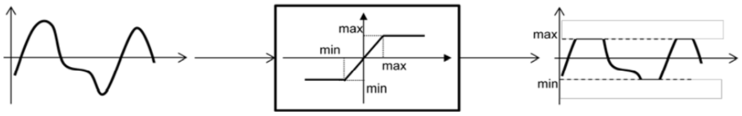
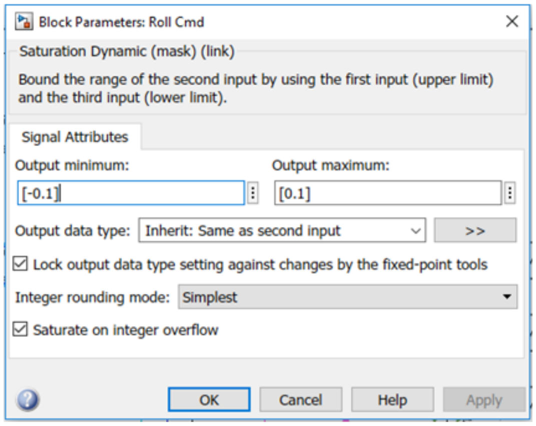


Figure 3.24: The non-linear phenomenon of saturation



Block Parameters: Roll Cmd

Saturation Dynamic (mask) (link)

Bound the range of the second input by using the first input (upper limit) and the third input (lower limit).

Signal Attributes

Output minimum: [-0.1]

Output maximum: [0.1]

Output data type: Inherit: Same as second input

☑ Lock output data type setting against changes by the fixed-point tools

Integer rounding mode: Simplest

☑ Saturate on integer overflow

Figure 3.25: The non-linear phenomenon of saturation bloc

3.4.5 Quadrotor subsystem

This subsystem can be divided in two part sensing part that provides the outputs of the system in order to build the control (altitude, roll, pitch , x, y) and rotors dynamic part where the speed commands generated by the control act on the rotors as well as the folding degrees of each arm as the next figure 3.26 shows up .

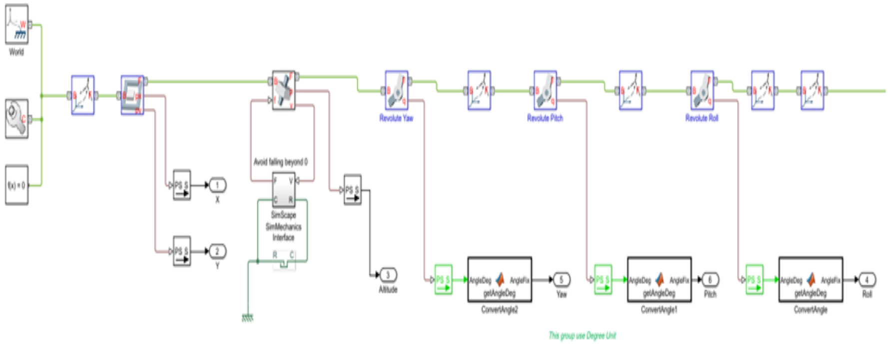


Figure 3.26: Sensing part of the quadrotor subsystem

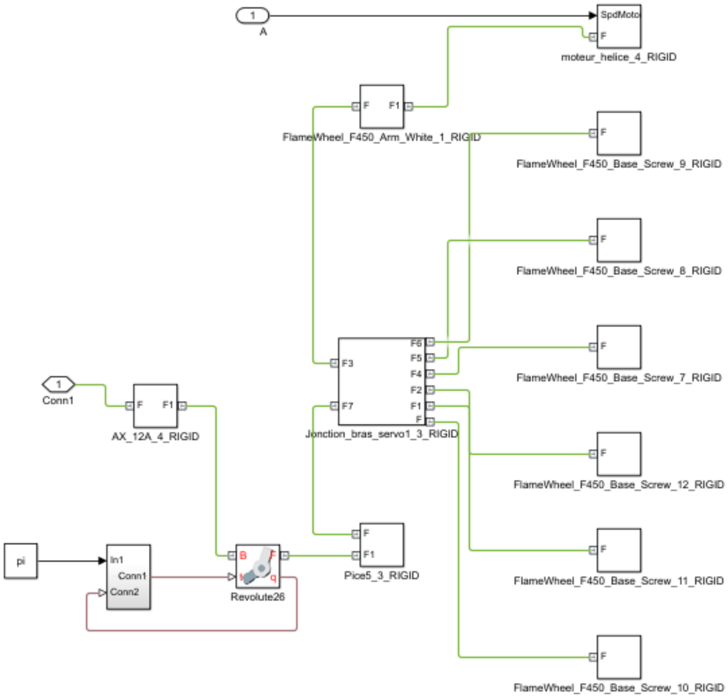


Figure 3.27: Example of a rotor dynamic in the numerical model

3.5 Mathematical model

In order to have accurate results it is important to compare them to a reference model, which is the mathematical model of a foldable quadrotor [66]

3.5.1 Quadrotor dynamics and control

This subsystem makes the big part of the quadrotor mathematical representation as it gathers both the dynamic of the quadrotor and it control.

Guidance Outer Loop Controller

Guidance Outer Loop Controllercontains the three desired positions as inputs (x_d, y_d, z_d) , the three current positions of the quadrotor (x, y, z) and their derivatives $(\dot{x}, \dot{y}, \dot{z})$ in addition to the roll angle ϕ and the pitch angle θ. The outputs are the controls on the three positions that are called (Ux, Uy, Uz).
This subsystem contains three subsystem one for Altitude Control, Longitudinal Control and Lateral Control. Each of three subsystem contains a simulink model obtained

from the control mathematical equations. Each subsystem is responsible of the regulation of one of the parameters (x,y,z), the following figures(3.29) shows the subsystems responsible for the outer loop quidance control.

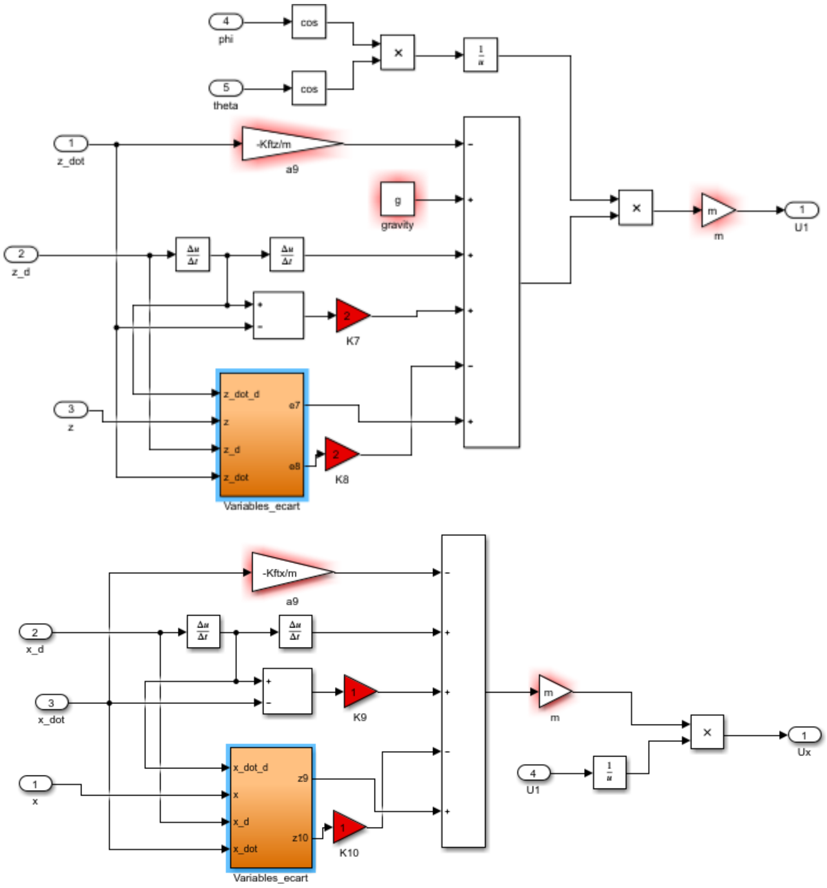


Figure 3.28: outer loop controls of (x, y) on the mathematical model

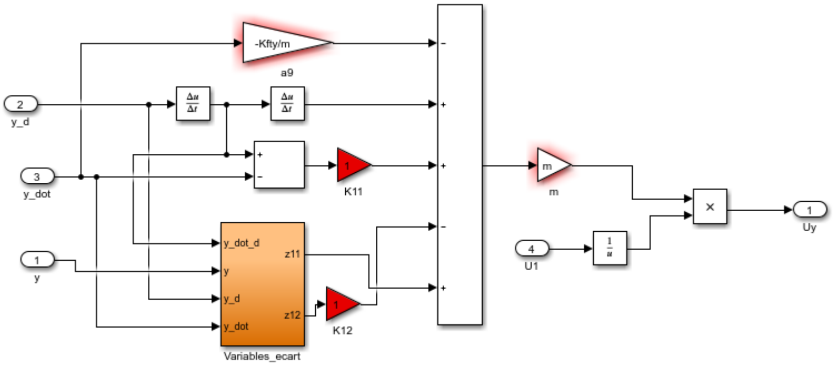


Figure 3.29: outer loop controls of z on the mathematical model

Desired roll and pitch computation

This subsystem is responsible for obtaining the pitch and roll angles (outputs) based on the desired yaw angle (ψ_d) and the control over the positions x and y (inputs)

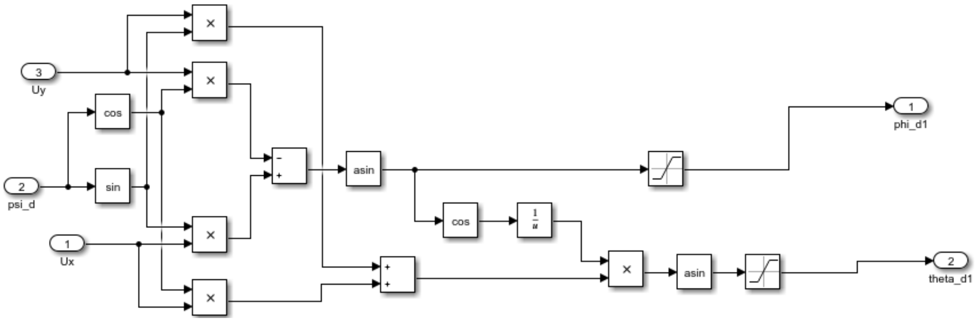


Figure 3.30: Bloc responsible for converting the x, y values into desired pitch and roll

Controllers

As there are pitch, roll and yaw angles dictates the motion of the quadrotor then those three angles needs to be controlled based on their mathematical equations the mathematical representation was concluded as the next figure 3.31 and 3.32 shows.

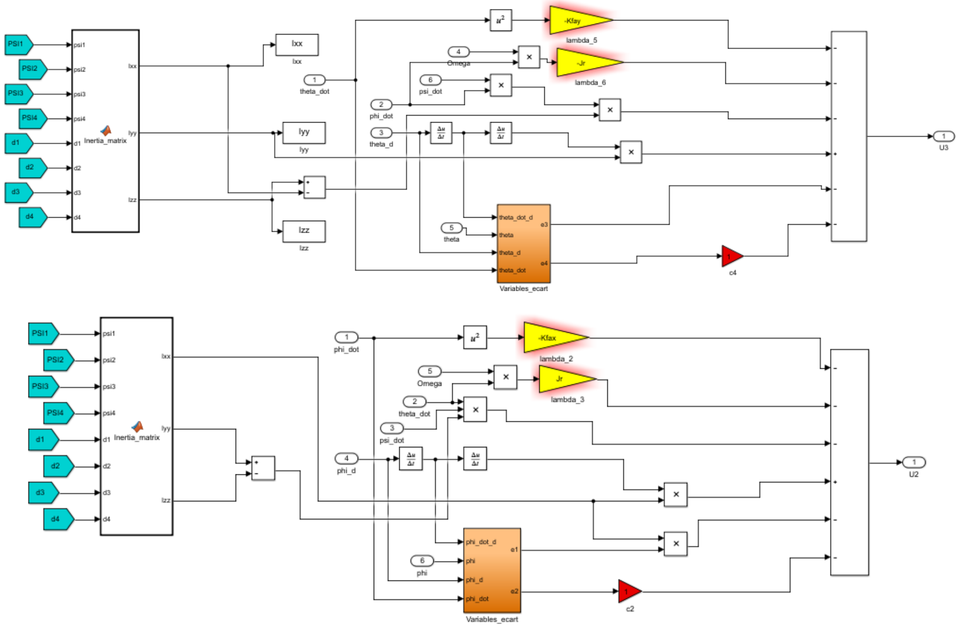


Figure 3.31: Pitch and roll control bloc

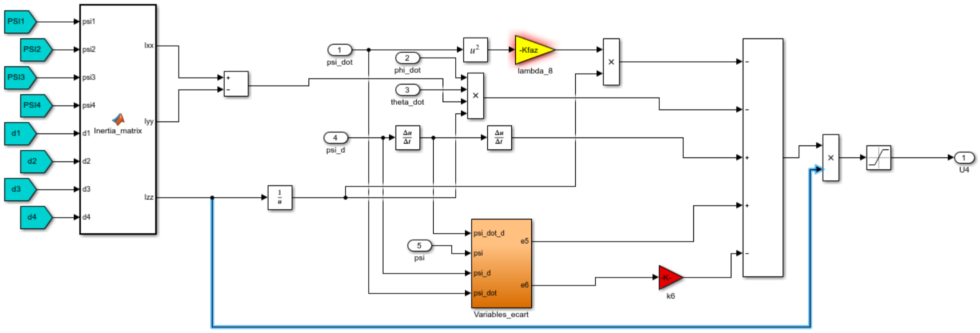


Figure 3.32: Yaw control bloc

QUAD ROTOR DYNAMICS

Based on the previous quadrotor equations that represent the dynamic of the drone as shown in the next figure 3.33, that sums the rotors dynamic the Euler angles and the placement of the quadcopter on the cordinates x and y.

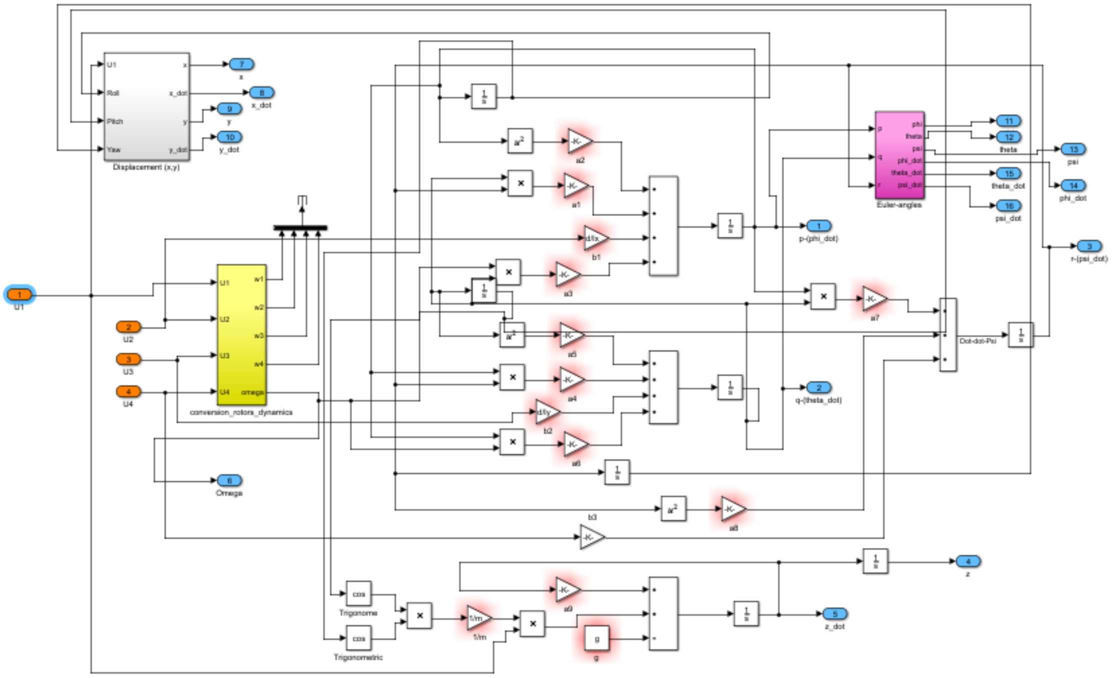


Figure 3.33: Bloc representing the dynamic of the quadrotor

3.5.2 Arms folding control

For the arm folding part of the mathematical model, is divided into four parts as the figure 3.34 shows with everyone representing the folding mechanism according to one of the configurations $(X, Y, T or O)$ successively what allows the quadcopter fold into different configurations while flying.

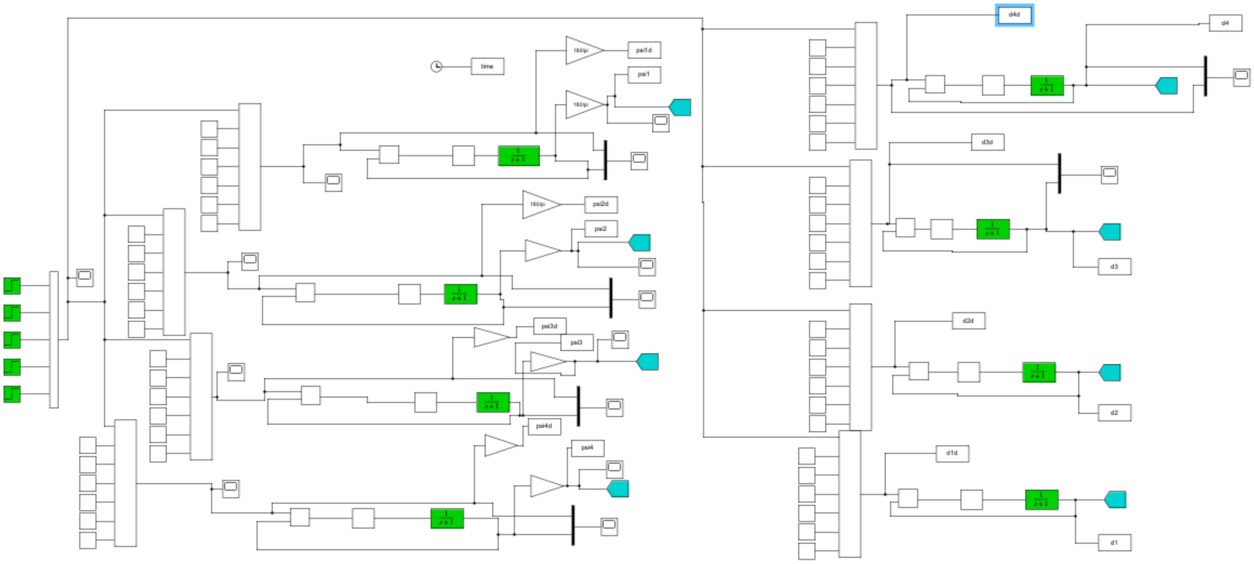


Figure 3.34: Bloc responsible of the control ofthe arms pivot

3.6 Conclusion

The numerical model and the mathematical model has almost the same structure and both using the same control which is the PID control.
Now once the numerical model is done, we will take steps towards making scenarios and attempting to fly the foldable quadrotor in different configurations.

Chapter 4

Foldable quadrotor model results

Contents

4.1 Introduction

After covering the descriptions of the models used both mathematically and numerically, experiments and tests are taken in hand to study the foldable quadcopter flying performances and the best control suited for this aerial robot.

4.1.1 Uploading inputs

For the next tests, four configuration will be used $(X, Y, T and O)$ and two trajectory scenarios a circular trajectory and a squared a half square trajectory on the Cartesian system (x, y).
On the tests on the numerical model only half the trajectories will be used because the system is quit complex what makes it takes a lot of time to generate results for every test. The following figure 4.1 shows the trajectory inputs of the numerical model.

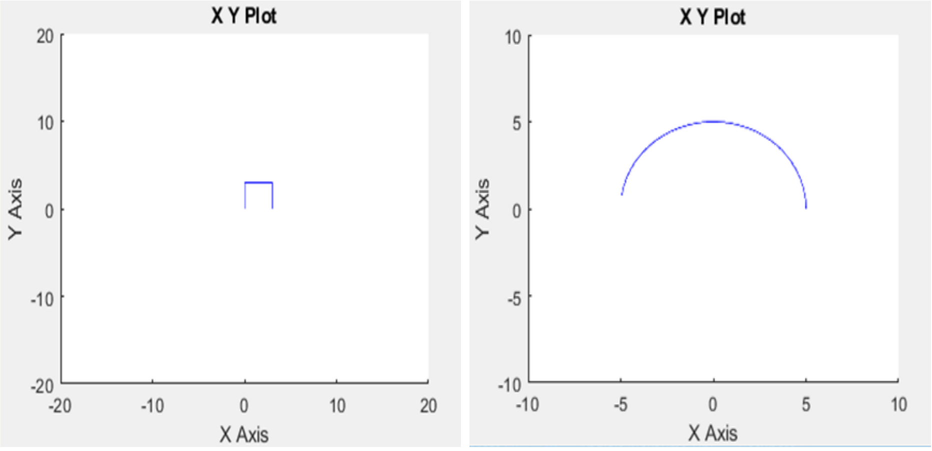


Figure 4.1: Half square and half circle signals that presents the trajectory input

4.2 Tuning the PID

Tuning the classical PID performances of each of the proportional integral and derivative action using the regulation rule as they go:

1. If the proportional gain X_p increases both speed and precision but it risks of having an unstable system (oscillating) if the proportional gain is sufficiently big.
2. If the integral gain T_i increases then the precision increases but the responding time decreases, and as for the proportional action if the integral gain is sufficiently big it risks of installing the system.
3. If the integral gain T_d increases then the stability increases as it plays the role of the filter, the speed increases without affecting the precision.

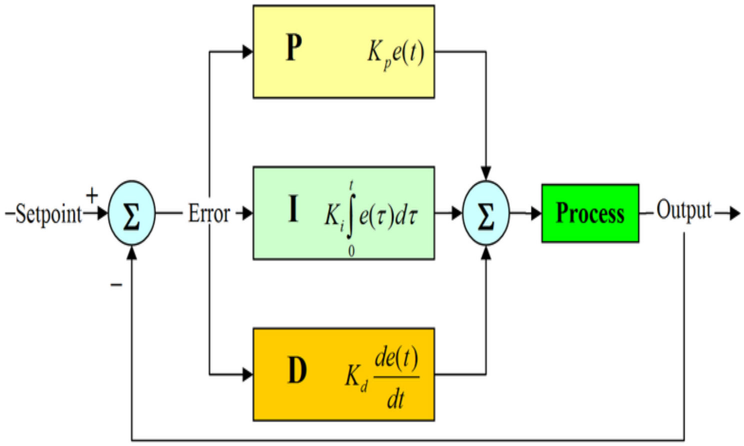


Figure 4.2: Explicit schema of the PID and a process

4.3 Results of the mathematical and numerical models

To best study the folding performances four configurations are tested while flying X, Y, T and O, following two trajectories, circular and linear or squared trajectory.

4.3.1 Mathematical model results

In order to test the PId control on the foldable quadrotor and it efficiency on keeping the steady state while flying with different configurations, two trajectories were tested the sinusiodal and the linear.

Results of the sinusoidal trajectory

For sinusoidal signal of 5 in amplitude and $0.1\ rad/sec$ as frequency for both X and Y trajectory inputs, 0 for the yaw $(\psi = 0)$ and a step signalof 10 for the Z trajectory input, the outputs resulted as follow.

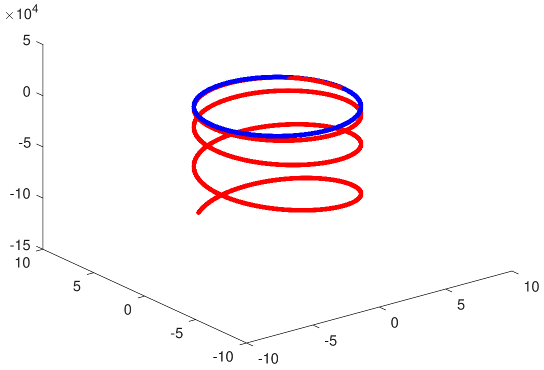


Figure 4.3: Output of the circular trajectory

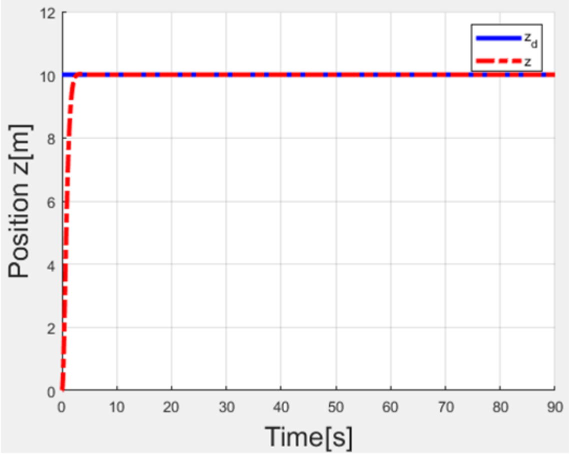


Figure 4.4: Altitude input and output signal of the mathematical model

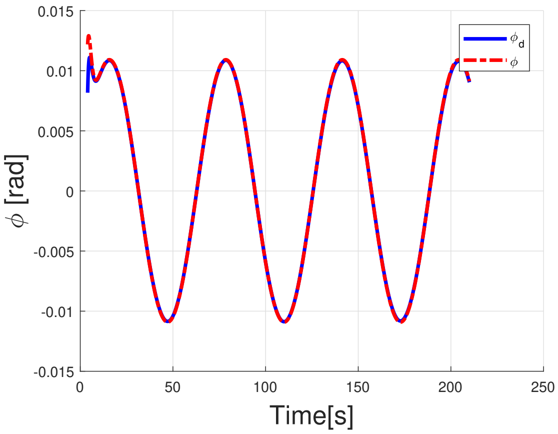


Figure 4.5: Outputs of the yaw angle on the left and the pitch angle on the right

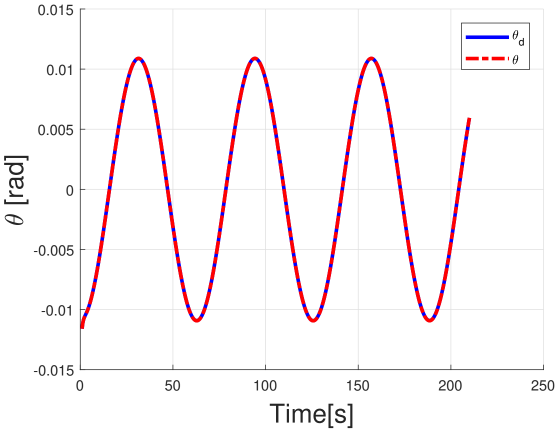


Figure 4.6: Roll input and output signal of the mathematical model

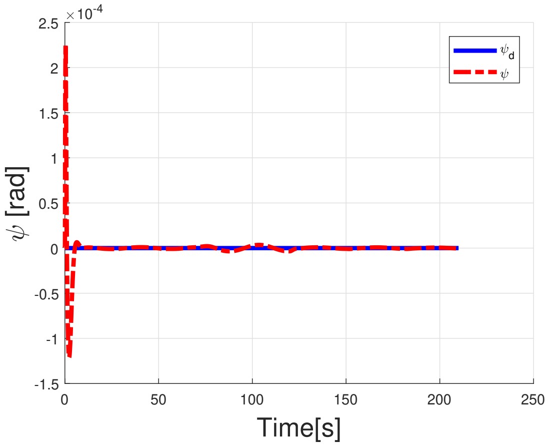


Figure 4.7: Pitch input and output signal of the mathematical model

Observations and discussions

We can notice on the trajectory output that the quadrotor kept spining until reaching the right altitude to follow the circular trajectory.

In time of $t = 1s$ the quadcopter reached the desired altitude.
The parameters outputs of the foldable quadcopter followed perfectly the input signals while switching from configuration to an other.
We can also notice the sinusoidal effect on the yaw output signal and that is caused by the non linear nature of the foldable quadrotor.
The over all results of the mathematical model of the foldable quadrotor while following a circular trajectory are almost with no errors or errors around the null value which proves the simple nature of the mathematical model and what made us look forward to see the numerical model results.

Results of the linear trajectory

The following results represents the parameters and the trajectory resulted from a linear (squared) trajectory applied as an input for the foldable quadrotor.

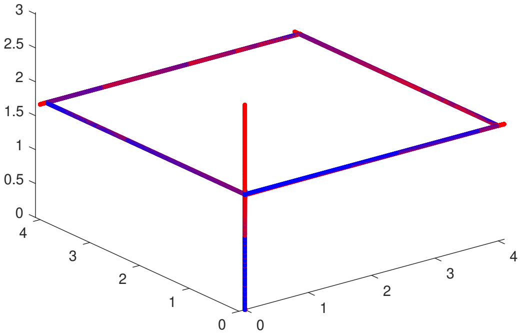


Figure 4.8: squared trajectory output

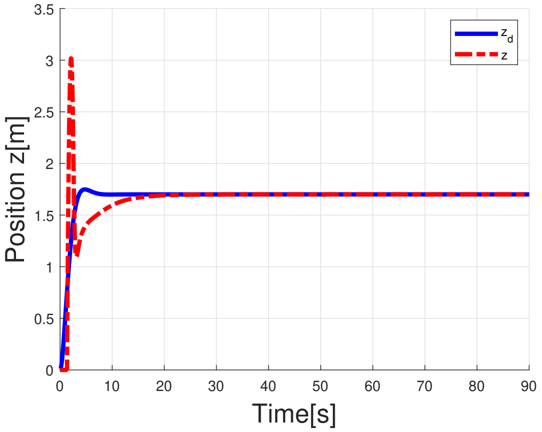


Figure 4.9: Altitude input and output signal of the mathematical model

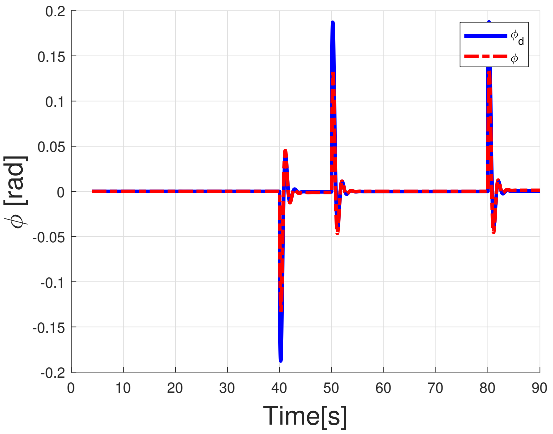


Figure 4.10: Roll input and output signal of the mathematical model

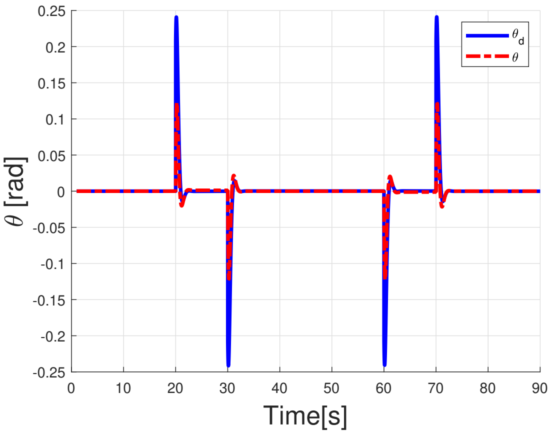


Figure 4.11: Pitch input and output signal of the mathematical model

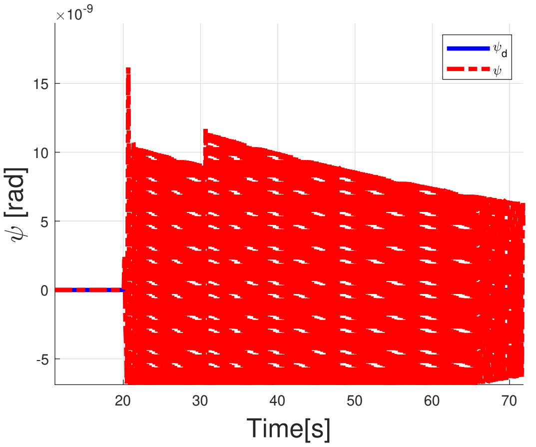


Figure 4.12: Yaw input and output signal of the mathematical model

Observations and discussion

- It is obvious that the output trajectory of foldable quadrotor succeeded to follow the squared trajectory, with some slight differences from the input trajectory.

- These differences are also expressed on the the altitude z display.

- For the rest of the parameters that represents the three angles(ψ, ϕ and θ), the outputs follow the inputs perfectly with some small differences on the peeking parts of the signals. these peeks represents the changing direction of the trajectory in other words the four angles of the squared trajectory.

- In the squared trajectory angles and when the quadcopter makes turns, the output of all three angles become not completely aliened with the inputs. We can notice that the amplitudes of the outputs during the peeking are smaller than the amplitudes of the inputs during peeking.

- That is explained by the delay of the output from it input.
  The peeking parts of the signals are done on a very short time, what does not allow the output reach the peek of the input which is -0.19 on the ϕ signal, but instead it follows the input signal back to the null value after reaching the peek of -0.1. Same explanation for the rest two displays of the angles signals.

4.3.2 Numerical model results

Configurations and matching the arms:
An online Motor mixing calculator [69] was used to get the mixing matrix (mixer settings) coefficients, this tool uses measured the distances between motors, that can be calculated using geometric laws.

X configuration

X configuration represents one of the classical quadrotor configurations figure 4.13 every arm makes a $\frac{\pi}{4}$ angle on the Cartesian system placed in the center of the servomotor.

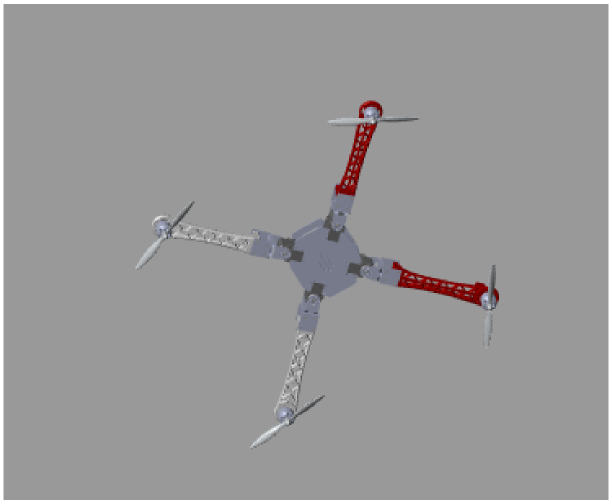


Figure 4.13: 3D design of the quadrotor with an X configuration

The fellowing mixing matrix is used to to represent the X configuration of the quadrotor.

$$\begin{bmatrix} -1 & 1 & -1 \\ -1 & -1 & 1 \\ 1 & 1 & 1 \\ 1 & -1 & -1 \end{bmatrix}$$

Circular trajectory:
The PID tuned values of the X configuration for a half circle trajectory are represented in the following table :

PID actions	P	I	D	N
ALT	30	10	15	10
Roll	15	1	0.01	10
Pitch	10	1	NON	1
Yaw	1	1	5	10

Table 4.1: PID values of the parameters for the X configuration on a circular trajectory

Results:
For the X configuration, the circular trajectory output followed by the quadrotor on x, y is represented as follow:

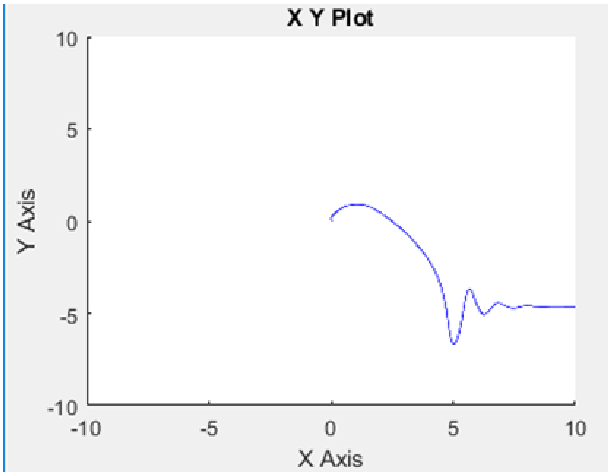


Figure 4.14: Outputs and inputs of the yaw,pitch, roll and altitude of the quadrotor on X configuration

The altitude, roll, yaw and pitch outputs are represented in the next figure 4.15

Figure 4.15: Outputs and inputs of the yaw,pitch, roll and altitude of the quadrotor on X configuration

Remark 1 *:*

- *The out put signals representing the yaw, roll, pitch and altitude are following their input signals (the yellow signals) with a static error on the altitude and the pitch.*
- *A half circular pattern is noticed on the x, y trajectory output, but it fails to follow it until the end.*
- *The output signal contains a small oscillation with an under and overshoot that is caused by the high values of the proportional values.*

Half square trajectory:

The PID tuned actions for the half square trajectory are represented in the following table:

PID actions	P	I	D	N
ALT	25	10	5	10
Roll	1	1	1	10
Pitch	10	2	NON	1
Yaw	3	1	5	10

Table 4.2: PID values of the parameters for the X configuration on a squared trajectory

Results:

For the X configuration, the squared trajectory output followed by the quadrotor on x, y is represented as follow:

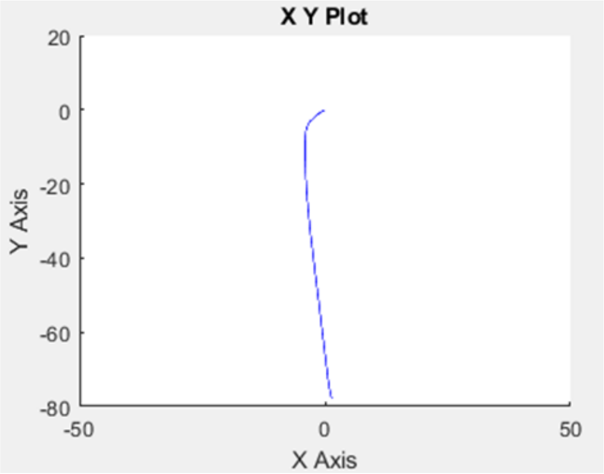


Figure 4.16: Outputs and inputs of the yaw, pitch, roll and altitude of the quadrotor on X configuration

The altitude, roll, yaw and pitch outputs for the squared trajectory are represented in the next figure 4.17

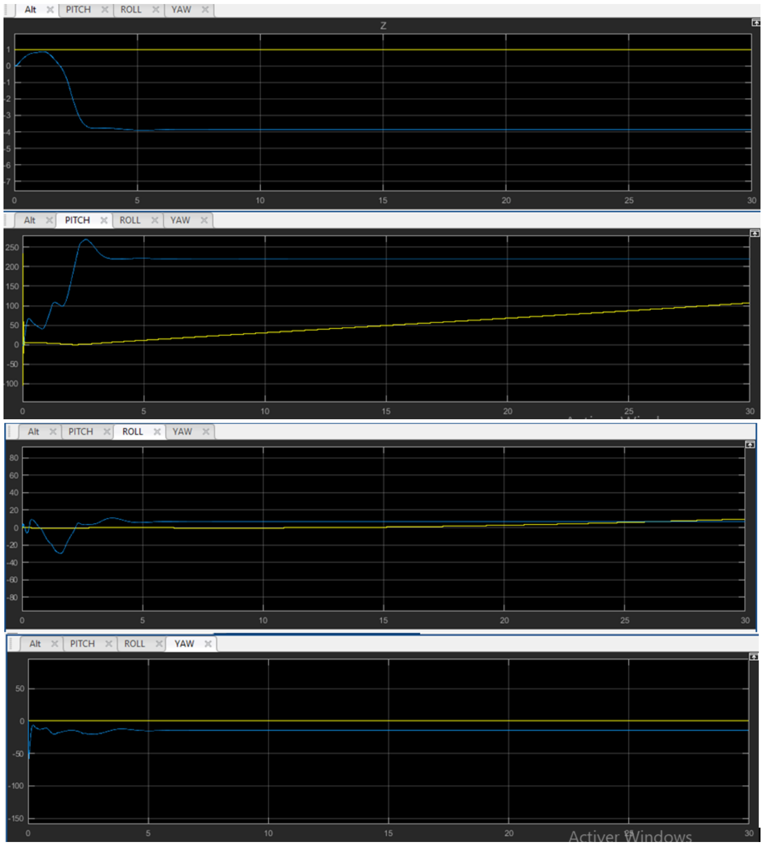


Figure 4.17: 3D design of the quadrotor with an X configuration

Remark 2 *:*

- *The quadrotor succeded to make the first turn of the half squared trajectory a not a sharp angle but not the second one, as it kept going in a straight line trajectory.*
- *Yaw, altitude and roll output signals are close to their input signals.*
- *Pitch is shifted to around 170.*

T configuration

T configuration is the configuration with the upper arms are wide open forming a 180 degrees angle and the bottom arms are parallel each making a 90 degree angle on the Cartesian system like shows the next figure 4.18.

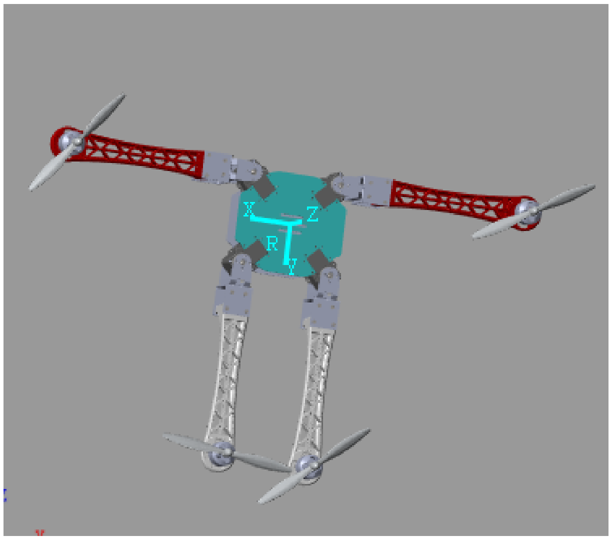


Figure 4.18: 3D numerical representation of the quadrotor on T configuration

the mixing matrix is represented as following:

$$\begin{bmatrix} -0.125 & 0.557 & -1 \\ -1 & -0.557 & 1 \\ 0.125 & 0.557 & 1 \\ 1 & -0.557 & -1 \end{bmatrix}$$

Half circle:

The PID values that allowed the right performance of the T configuration is,

PID actions	P	I	D	N
ALT	10	1	5	0.1
Roll	50	15	0	1
Pitch	-1	NON	0	1
Yaw	0.1	0.1	0	10

Table 4.3: PID values of the parameters for the T configuration on a circular trajectory

For the T configuration, the circular trajectory output followed by the quadrotor on x, y is represented as follow:

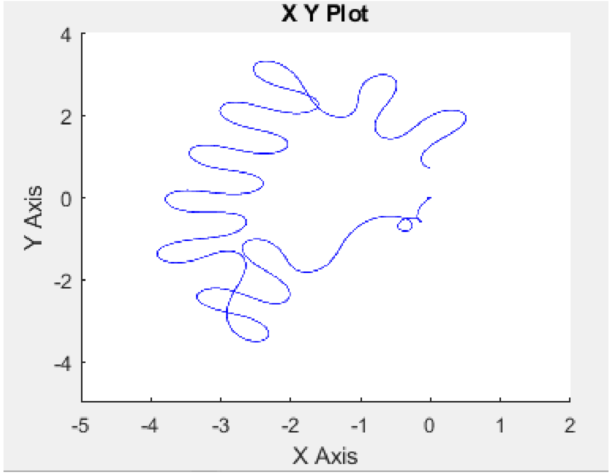


Figure 4.19: (x, y) trajectory output of the quadrotor on T configuration

The altitude, roll, yaw and pitch outputs for the squared trajectory are represented in the next figure 4.20.

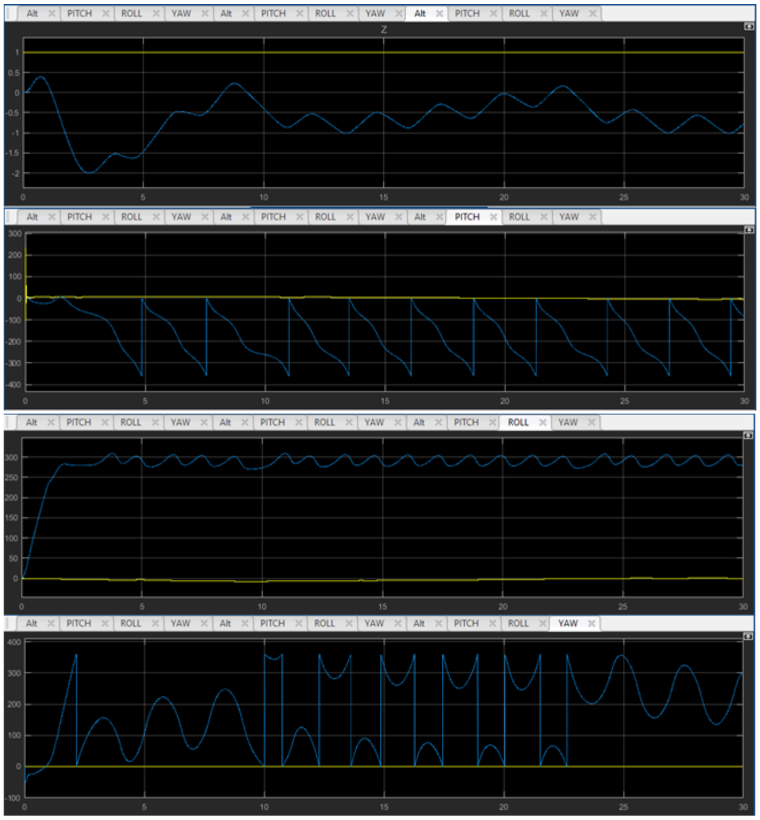


Figure 4.20: Outputs and inputs of the yaw,pitch, roll and altitude of the quadrotor on T configuration

Remark 3 *:*

- *The T configuration was a bit hard to stabilize and that is seen in the sinusoidal motion that the quadrotor is having.*
- *Thus the wavy motion that the quadcopter is having it is clearly following a circular pattern.*
- *The wavy motion is also expressed on the thee angles and altitude signals.*

PID actions	P	I	D	N
ALT	30	10	15	10
Roll	5	1	0.01	10
Pitch	10	NON	1	1
Yaw	1	1	5	10

Table 4.4: PID valuesof the T configuration on a squared trajectory

Results:
For the T configuration, the squared trajectory output followed by the quadrotor on x, y is represented as follow:

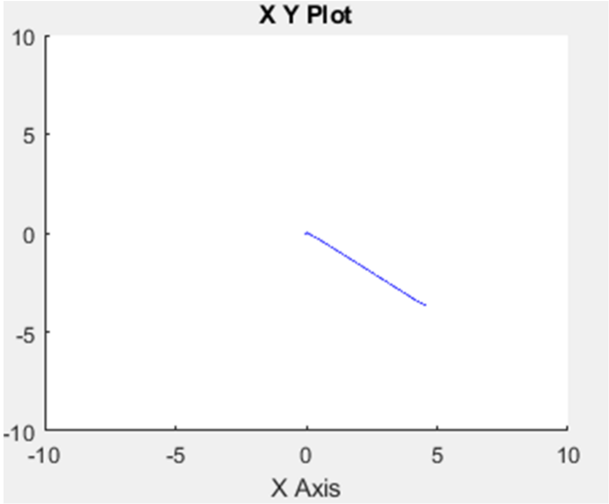


Figure 4.21: (x, y) trajectory output of the quadrotor on T configuration

The altitude, roll, yaw and pitch outputs for the squared trajectory are represented in the next figure 4.22.

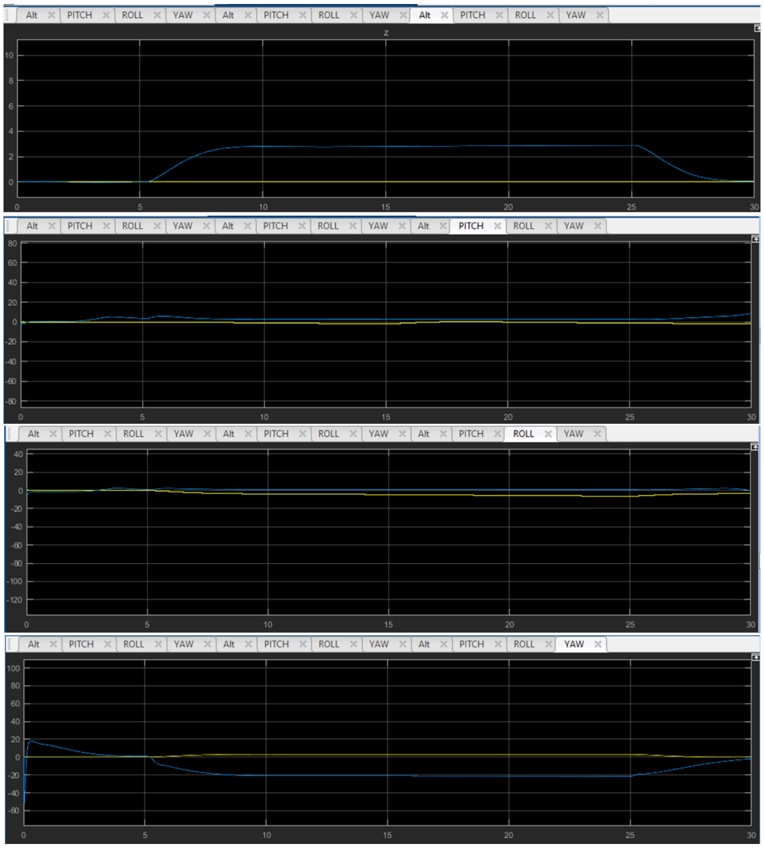


Figure 4.22: Outputs and inputs of the yaw,pitch, roll and altitude of the quadrotor on T configuration

Remark 4 *:*

- *T configuration can loses is stable state easily despite that it managed to follow slightly the patter of the inputs.*
- *This configuration failed to generate the angles on it (x, y) output trajectory except for a small one at the start and kept a straight line for the rest of the trajectory.*
- *Despite the fail of the right trajectory fellow the angles and the altitude outputs did really good following their inputs.*

Y configuration

This configuration has an X configuration upper side and a T configuration on the down side as shows the following figure 4.23.

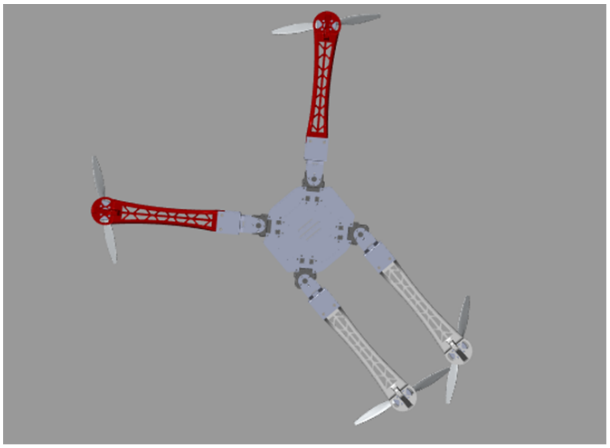


Figure 4.23: 3D design of the quadrotor with an X configuration

The mixing matrix of the Y configuration is represented as following:

$\mathrm{R_x}$=

$$\begin{bmatrix} -0.153 & 1 & -1 \\ -0.918 & -1 & 1 \\ 0.153 & 1 & 1 \\ 0.918 & -1 & -1 \end{bmatrix}$$

PID actions	P	I	D	N
ALT	NON	0.001	NON	NON
Roll	100	1	50	1
Pitch	0.01	NON	0	1
Yaw	100	NON	NON	NON

Table 4.5: PID values of Y configuration on a circular trajectory

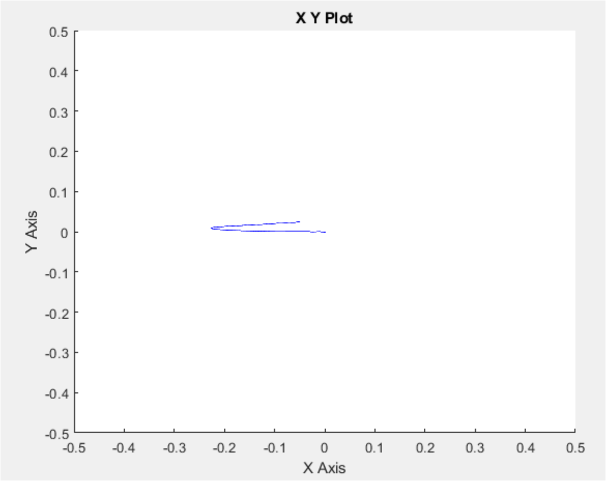


Figure 4.24: (x, y) circular trajectory output of the quadrotor on Y configuration

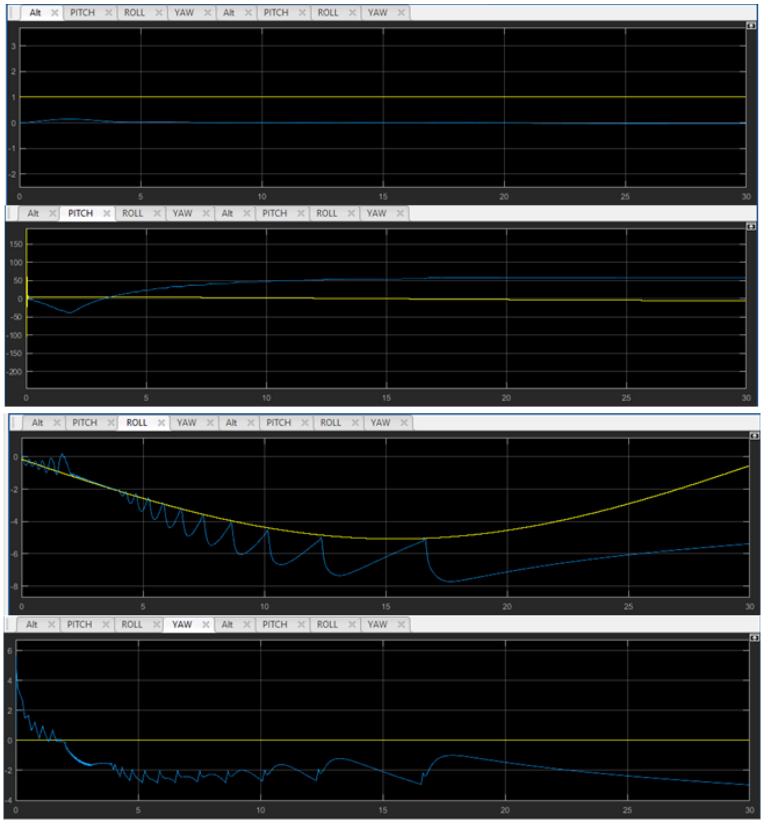


Figure 4.25: Outputs and inputs of the yaw,pitch, roll and altitude of the quadrotor on Y configuration

Remark 5 :

- *The Y configuration had a half circle trajectory with a narrow angle.*
- *The altitude and the three angles (yaw,pitch and roll) succeded to fellow their input*

trajectories with an oscillation for the roll and yaw.

PID actions	P	I	D	N
ALT	10	1	5	10
Roll	0.01	1	10	10
Pitch	0.001	NON	0	0.01
Yaw	100	1	0.01	10

Table 4.6: PID values of Y configuration on the squared trajectory

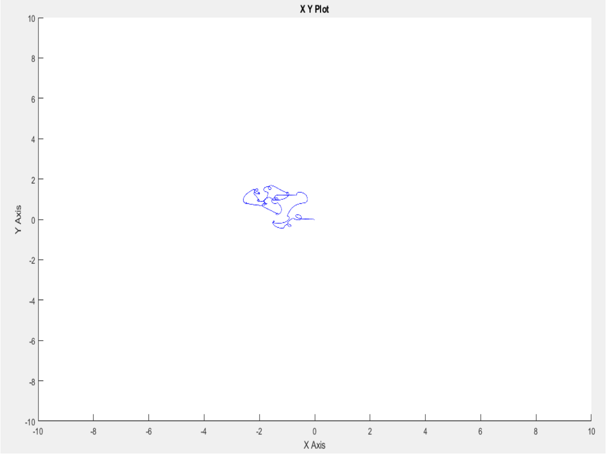


Figure 4.26: (x, y) squared trajectory output of the quadrotor on Y configuration

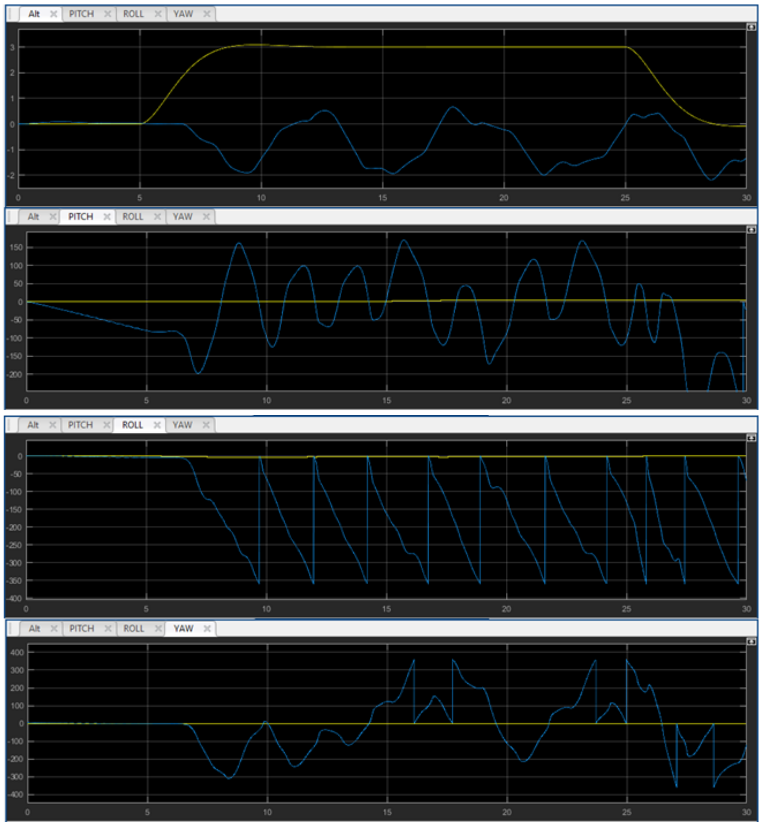


Figure 4.27: Outputs and inputs of the yaw,pitch, roll and altitude of the quadrotor on Y configuration

Remark 6 *:*

- *The* (x, y) *output trajectory started by having a straight line and went random (unsteady trajectory) once it reached the angle turn.*
- *Same for the altitude and the angles, it started steady with a small error until reaching around time 7 seconds when all four output signals oscillated.*

O configuration

the O configuration has all arms folded on the right or the left with each arm making a 180 degrees on it Cartesian system, as shows the next figure 4.28.

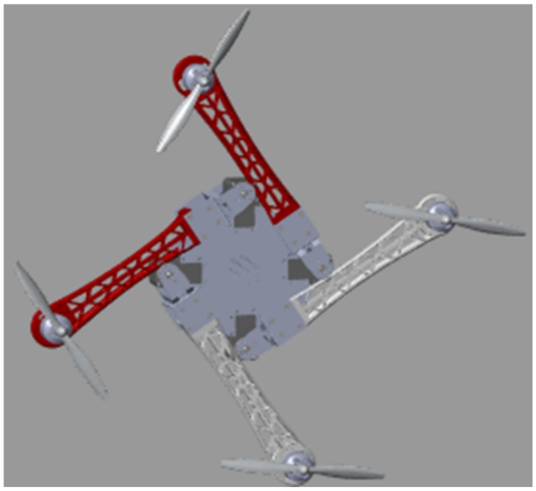


Figure 4.28: (x, y) trajectory output of the quadrotor on Y configuration

The mixing matrix is represented as follow:

$$\mathrm{R_x} = \begin{bmatrix} -1 & 0.801 & -1 \\ -0.801 & -1 & 1 \\ 1 & 0.801 & 1 \\ 0.801 & -1 & -1 \end{bmatrix}$$

PID actions	P	I	D	N
ALT	30	10	25	10
Roll	15	1	0.01	12
Pitch	15	NON	1	1
Yaw	3	1	5	10

Table 4.7: PID values of O configuration on the circular rajectory

Results of the numerical model of the foldable quadcopter with a half circle trajectory input applied on an O configuration, are represented as follow:

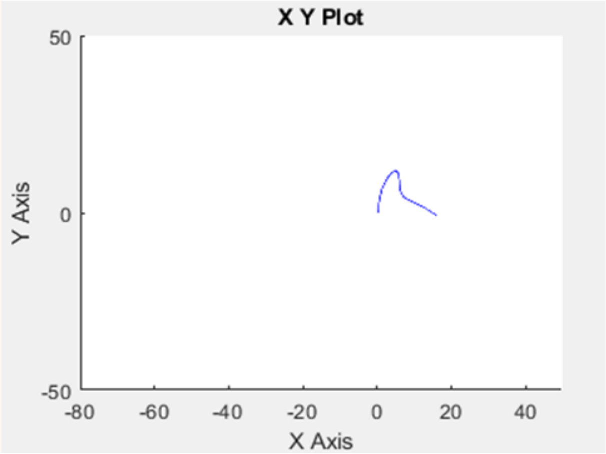


Figure 4.29: (x, y) trajectory output of the quadrotor on O configuration

The altitude, roll, yaw and pitch input and output signals for the squared trajectory applied on an O configuration of the foldabl equadrotor are represented in the next figure 4.30

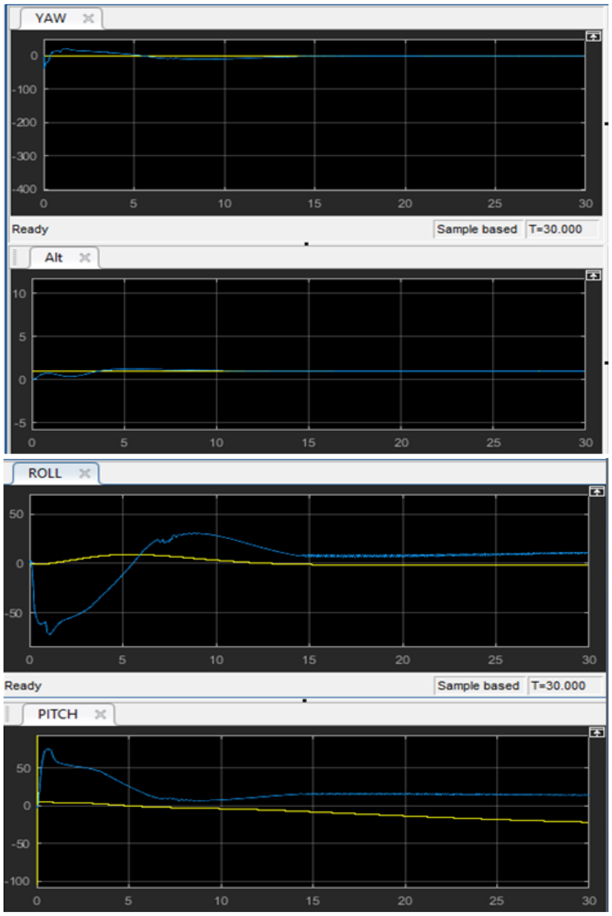


Figure 4.30: Altitude, roll, yaw and pitch input and output signals

Remark 7 *:*

- *The (x, y) trajectory output fellowed nicely the circular trajectory input at first but it went straight after a while.*
- *As for the altittude and the three angles which fellowed thier inputs with a small error, an overshoot is notice on the pitch output signal caused by the derevitive action on the altitude.*
- *A delay is noticed on the roll output angle.*

square trajectory.

PID actions	P	I	D	N
ALT	30	10	25	10
Roll	0.5	0.1	0.01	10
Pitch	15	NON	5	1
Yaw	3	1	5	10

Table 4.8: PID values of O configuration on the squared trajectory

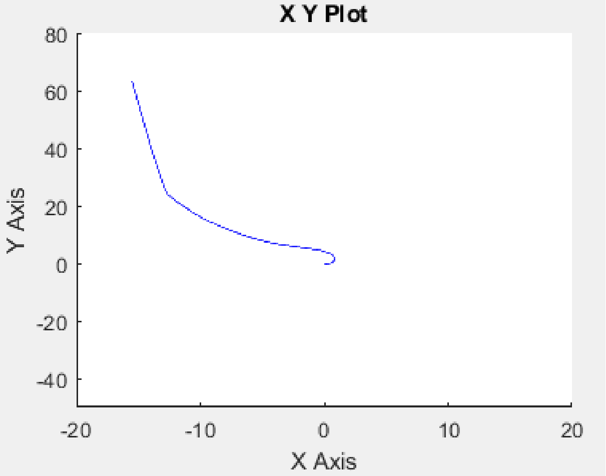


Figure 4.31: (x, y) trajectory output of the quadrotor on O configuration

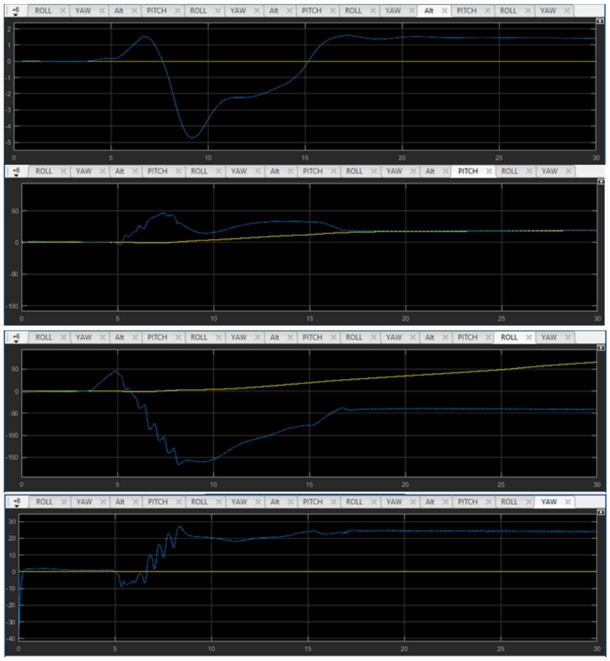


Figure 4.32: Altitude, roll, yaw and pitch input and output signals

Remark 8 *The trajectory output succeded to have one angle, but it is not a very sharp one. Having the angle is equivalent in time of losing the steady state between t=5s to t=10s. For this case the pitch is the most precised.*

4.3.3 Discussion

•Y and T configurations were the hardest configurations to tune as these configurations lose their steady state so easily.
•Each angle affect the other due to the non linear nature of the system what made it a hard task to tune the four pid controllers.
•The mathematical results were better than the numerical ones and that due to the simplicity of the mathematical model and the simplifications that it has in the other hand the numerical model is closed to to the real model and that can add the physical errors of the model as an obstacle.
•It is so difficult and nearly impossible to set all the outputs on the right value (the inputs) due to the non linear nature of the system. •The static error resulting a shifted output value from it input example of the altitude output for the Y configuration on a circular trajectory, can be corrected using an integrator.

4.4 Conclusion

The numerical model is a great way to test any robotic tool as it can save us a lot of time and the physical material but it can also be so slow if the model is a little complicated.

Despite the differences between the two models results due to the difference in models, all the results had a steady state of the quadcopter on both trajectory senarios.
The foldable quadrotor tend to follow the pattern of the input trajectory even that it didn't follow it exactly on the numerical model but the results was an enough proof of the successful functioning of the horizontal rotating arms quadcopter.

General conclusion

Through the work presented in this thesis, I have proved the possibility of making a foldable quadrotor, using both numerical and mathematical models.
The models performed different configurations, allowing the quadcopter to be more flexible and environment adaptive.
Tuning the PID was a bit of a challenge due to the non linear nature of the foldable quadcopter, but despite that, the experiences on the numerical model gave results that proved the success of the foldable quadrotor. Even that the results of the numerical did not much the ones of the mathematical model but over all results demonstrated a steady state. What encourages us to work on the control of the foldable quadcopter.
Developing a control law for the horizontally rotating arms quadrotor is an interesting next step of this study that can take the results found in these thesis to make a suitable control.

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ملخص:

تزداد الحاجة إلى مركبات الطائرة بدون طيار أكثر فأكثر كل يوم نظرًا لقدرتها على الوصول إلى الأماكن والقيام بالمهام التي يصعب على الإنسان الوصول إليها والقيام بها

يمكن للطائرة بدون طيار أن تتحدى بعض العقبات مثل العمر القصير للبطارية أو الظروف البيئية الخاصة (العوائق ، الطقس القاسي ...) أو مجرد التحرر من .درجات الحريةالست التي تعيق تحركها في كل اتجاه

و تؤدي حتى إلى فشلها التام يمكن لهذه الظروف الخاصة لبيئة عمل الطائرات بدون طيار أن تمنعها من القيام بمهامها أو العمل بشكل صحيح

.لتجنب مثل هذه الأضرار ، كان لدى العلماء والمهندسين الرغبة في صنع نوع جديد من الطائرات بدون طيار ، الطائرات بدون طيار القابلة للتحويل

الطائرات بدون طيار القابلة للتحويل أو الطائرات بدون طيار القابلة لإعادة التشكيل هي الطائرات بدون طيار التي يمكنها تغيير شكلها من أجل التكيف مع البيئة .الخارجية

اخترنا دراسة الطائرات بدون طيار القابلة للطي بشكل أكثر تحديدًا ، والتي تدور أذرعها الأربعة أفقيًا. باستخدام كل من النماذج الرياضية والرقمية لتمثيل التكوينات المختلفة للطائرة الرباعية القابلة للطي ، حصلنا على نتائج مختلفة قليلاً كما كان متوقعًا، بسبب استخدام نموذجين مختلفين. ولكن الأشياء المشتركة حول النتائج هي أن نتائج كلا النموذجين تمثل حالات ثابتة للطائرات الربعاية بدون طيار في تتبع مساراتها وكلا النموذجين إلى اتباع نمط المسار المعطى كمدخل

Abstract:

Unmanned Ariel vehicles are needed more and more everyday due to their ability to reach places and do tasks that are hard for human to reach and to do.

Drone can face some challenges such as the short life of the battery or the environmental special conditions (obstacles, rough weather…) or just to be liberated from it six degrees of freedom.

These special conditions of the drone working environment can prevent it from doing it tasks, functioning correctly or even lead to it total fail.

To avoid such damages scientists and engineers had the urge to make some new kind of drones, the transformable drones.

Transformable drones or reconfigurable drones are the drones that can changes their morphology In order to adapt with the external environment.

We chosed the study of foldable drones more specifically horizontally rotating arms quadrotor. Using both mathematical and numerical models to represents the different configurations of the foldable quadcopter, we obtained little different results what was expected due to the use of two different models but the common things about the results is the results of both models represent steady states of the quadcopter and both model results tend to follow the pattern of the trajectory given as an input.

Keywords:
Foldable quadrotor- transformable drones- numerical model- mathematical model- PID

Résumé :

Les véhicules Ariel sans pilote sont de plus en plus nécessaires chaque jour en raison de leur capacité à atteindre des endroits et à effectuer des tâches difficiles à atteindre et à accomplir pour les humains.

Le drone peut faire face à certains défis tels que la courte durée de vie de la batterie ou les conditions environnementales particulières (obstacles, mauvais temps) ou simplement se libérer des six degrés de liberté.

Ces conditions particulières de l'environnement de travail du drone peuvent l'empêcher d'effectuer ses tâches, de fonctionner correctement ou même de conduire à son échec total.

Pour éviter de tels dommages, les scientifiques et les ingénieurs les scientifiques et les ingénieurs ont fabriqué un nouveau type de drones, les drones transformables.

Les drones transformables ou reconfigurables sont les drones qui peuvent changer de morphologie afin de s'adapter à l'environnement extérieur.

Nous avons choisi l'étude de drones pliables plus précisément à bras quadrotor à rotation horizontale. En utilisant à la fois des modèles mathématiques et numériques pour représenter les différentes configurations du quadcopter pliable, nous avons obtenu des résultats peu différents, ce qui était attendu en raison de l'utilisation de deux modèles différents, mais les points communs des résultats sont que les résultats des deux modèles représentent des états stables du quadcopter et les deux résultats du modèle ont tendance à suivre le modèle de la trajectoire donnée en entrée.