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Facultad de Ingeniería Mecánica y Eléctrica

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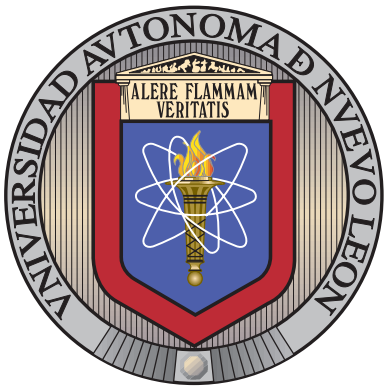

Design of convertible UAV with hover and cruise flight capabilities

por

Edgar Ulises Rojo Rodríguez

como requisito parcial para obtener el grado de

maestría en ingeniería aeronáutica

con orientación en Dinámica de Vuelo

Noviembre 2022

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Posgrado

Los miembros del Comité de Evaluación de Tesis recomendamos que la Tesis "Designo of covertible UAV with hover and cruise flight capabilites", realizada por el estudiante Edgar Ulises Rojo Rodríguez, con número de matrícula 1615331, sea aceptada para su defensa como requisito parcial para obtener el grado de Maestría en Ingeniería Aeronáutica con Orientación en Dinámica de Vuelo.

El Comité de Evaluación de Tesis

Dr. Octavio García Salazar
Director

Dr. Luis Amézquita Brooks
Revisor

Dr. Luis Arturo Reyes Ososrio
Revisor

Dr. Edmundo Javier Ollervides Vázquez
Revisor

Vo.Bo.

Dr. Simón Martínez Martínez
Subdirector de Estudios de Posgrado

Institución 190001

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Ciudad Universitaria, a 09 de diciembre del 2022.

For my parents who have always
encouraged me to reach higher,
and to my brother who has always
inspired and supported me.

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Abstract

Edgar Ulises Rojo Rodríguez.

Candidate for degree of: Maestría en Ingeniería Aeronáutica con orientación en Dinámica de Vuelo.

Universidad Autónoma de Nuevo León.

Facultad de Ingeniería Mecánica y Eléctrica.

Research title: Design of convertible UAV with hover and cruise flight capabilities.

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Objectives and method of study: The general objective of this research is to design and develop a convertible UAV prototype with hovering and high-speed cruise flight with auto sustainability capabilities,
As specific objectives we propose:

- To design conceptual prototypes.
- To establish a flexible control scheme.
- To develop 3 prototypes with unique characteristics and integration of them into final application.
- To optimize manufacture parameters of prototypes.

- To design a hybrid configuration (rotatory and fixed wing dynamics).
- To perform real time validation.

For those objectives, method of study was based on the qualitative and quantitative methods, where the complete design, is based on mathematical models for design, manufacture and implementations aided by analytical methods for adaptations of physical limitations, control schemes and dynamics inversion integration. The whole scheme integrates and validates system performance, evaluating orientation and position tracking accomplish.

CONTRIBUTIONS AND CONCLUSIONS : The main contribution of this research involves a novel design of aircraft which allow hybrid capabilities and advanced performance for precision farming, terrain photometer and medium range mission of sensible package, developing multi-phase missions.

Advisor's signature : _____

Dr. Octavio García Salazar

Chapter 1

Introduction

1.1 Background

Unnamed Aerial Vehicles (UAVs) become a great research interest due to their versatility and variety of applications [9], is important to mention that UAVs become from the XIX century, the first UAV belongs to Austrian forces, using a balloon carrier, register as the first air power in naval aviation [13].
At beginning of the history of UAVs, these were imprecise and ineffective due to their technology, over time this was corrected, allowing precise flights and effective formations to emerge as an active research field [2], the first active pilot-less aircraft were built during World Ward I, used to attack zeppelins, British drone weapons are the first reported to been used for that kind of military missions [13].

At actual date, UAVs are common, every person could afford one, thanks to electronics miniaturization and manufacturing process, allowing them to be remotely piloted and used for different activities, more common are photography, in that sense, quadcopters are the configuration of UAV selected by civilians to perform that kind of activities [11].
Civilians especially use quadcopters by their capabilities to perform flight in closed

spaces and have the possibility of hover [11], also a simpler configuration would allow to have fewer failures [20] whereas quadcopters are UAVs with just dependency on their rotors, electrical machines with a high lifespan and a low failure ratio [41].

It is important to mention that being the most popular configuration does not make them the greatest, whereas in the UAVs field it depends on applications; there are more configurations of UAVs, and more common are fixed wing, rotatory wing and recently convertible ones [62].

Actual technology allows to expand rotatory wings field, classically just fixed wing could be implemented, due to fast dynamics of rotatory wings, which could not be sense and mitigated by the system, making a damped system ideal for implementation, and also others aspect as safe operation in case of electronics failure and simpler actuators required.

Aircraft capabilities are aspects to consider to create a missions for UAVs, in that sense is important to create a delimitation, which would be the use of each aircraft in order to perform an acceptable mission [2], these requirements are established by some factors, those would be engaged on UAV section, generally, those are endurance, speed and environmental conditions.

The first aspect to consider is related to energy consumption, this could be studied from different approaches, the first one related to efficiency, and the second in energy capacities; for efficiency it is focus on how much energy our aircraft use, commonly propulsion is the main energy demand component, becoming into the main core of the study, and for second aspect it is examined the way that our aircraft could carry with fuel reserves [20], both of these aspects were limited by technology.

Principal limitations were motors, which used to be inefficient, also fuel cells cannot carry too much fuel, or in the case of electric approaches, the battery could not have high-density cells to store more energy, that aspect reduces endurance, limiting applications for small aircraft; this problem is attack by the implementation of more efficient components [20], propellers optimization [59], and control energy reduction [11], [7],[40], those advances allow to create newer configurations, as well as expand missions that could not be performed with classic configurations of UAVs.

Long endurance and high-speed missions used to be just for fixed-wing configurations, where aerodynamics allow them to fly more efficient than rotatory ones [1], and this is reflected in longer missions, this inspired two different approaches, rotatory wings efficient research [59], but also a different configuration implementation, convertible ones, those are mixed, both configurations to have a combination of capabilities [10], [24], [9]; energy, technology, and mission endurance are the principal aspects that governed the advance of UAVs.

According to the application, these UAVs have some derivations, due to security [41] or to manufacture process [40], making a huge panorama of configurations, more common are quadcopters, hexacopters, octocopters, tricopters, convertible approaches, and fixed-wing [12], [1], [62], the more popular is the quadcopter configuration, aided by its mechanical simplicity and interest on them due to interior and closed maneuvers capabilities.

1.1.1 Quadcopter UAV

This configuration of aircraft is based on four groups of rotors that allow differential forces, which in a control sense it is used as outputs to perform the flight [7]. This configuration is implemented by civilians at quotidian missions, where they are simpler and do not require redundancy or strict rules to perform them, there are just limited by restricted zones, autonomy, and civilian security [11].

Quadcopters are commercially distributed by DJI, Parrot, Syma, MicaSense, Pix4D, 3DR, and others, those manufacturers popularize and simplify the use of drones in the civilian field, some implementations as fold-able, repairable, and upgradeable are some characteristics that popularize this small factor aircraft, also bigger ones become popular [49].

The real factors that allow civilians to use UAVs are related to control and sensing field, there are used for flight assistance as well as maneuvers implementations, giving the possibility to be piloted by precipitant pilots and that allow the possibility to create unique applications, related to inspection and photography field [62].
Modern quadcopters become popular in 1990, and early 2000s, when some civil kits become popular and useful, in the research field, the Draganflyer quadhelicopter gained some recognition thanks to its capabilities and use in the movies field, and some other prototypes were also presented, and commercialized, but it was not stable, capable, and flexible as this platform.
XIX century become the quad-era, it has grown in popularity among researchers and hobbyists, especially in 2010 when Parrot released "AR.Drone" the first commercially successful ready-to-fly consumer drone. Historically, some research laboratories and universities started projects with quadrotors, to develop autonomous flight [43], where Stanford, Pennsylvania, Compiegne, Cornell University, and MIT, were the most important developers at this point on quadcopters, they use different approaches to control, some of there were reinforcement learning, backstepping, PID, visual feedback MBPC and H∞. [14]
This configuration also has its limitations, some maneuvers are unperformed, energetic efficiency and payloads limit this aircraft configuration, which creates the necessity of other configurations that could also handle actual quadrotor missions, emerging the convertible aircraft field, also manipulators and stabilizers are used at the quadrotors platform to expands its mission coverage, but this add-on creates some aerodynamic and efficiency limitations, as well as complex structures that could be replaced by others aircraft, at this case convertibles ones, are proposed.

1.1.2 Convertible Aircraft

Convertible aircraft or hybrid aircraft, are models that change states on its actuators or in its structure, there are considered as the same approach and give more

characteristics than conventional aircraft.

This configuration of aircraft begins in the 50s century, Lockheed XFV was presented, an american experimental tail-sitter prototype from U.S. Navy, demonstrating some dynamics, and mechanical complex of this kind of configuration, also technological limitations were discovered, this lack of technology limited the evolution of this aircraft into others projects, especially into UAVs were miniaturization is one of the most crucial factors, and by this time it was not possible.

Other convertible aircraft were designed and implemented, such as NASA VERTOL-z2, Curtiss-Wright X-19, Bell-Boeing V-22, F35-B SVTOL, Boeing Phantom Swift X- Plane Concept, Wingcopter, Airbus Vahana, and others [24], those selected by it is historical importance, were some of them become into production aircraft and demonstrate the capabilities and newer approaches that a convertible aircraft could handle. For this research Bell-Boeing V-22 and Boeing Phantom Swift X-Plane Concept are selected as background inspiration, both create interest in this aircraft configuration and confidence in conducting this kind of project.

Actual research creates lots of prototypes, from conventional structures based on quadcopters [50] [46] [15], to others unconventional as tricopters or multirotor with geometries not based on "X" or "+", for this specific research there are use those one base on tricopters, a configuration that allows us to attach the structure for fixed wing, some authors already create prototypes with this inspiration [60], also tilting movement of rotors are also consider on others prototypes [34], [61], [55], [10].

Convertible aircraft were introduced since small UAVs become popular [51], at this point, the prototyping phases were unperformed or develop with shortcomings, those developments were conducted as mathematical models [32] without implementation or incomplete experiments, those lacks were especially due to technology miniaturization.

The first public reports of convertible UAVs that were useful belonged to a control approach, which establishes a methodology for this kind of aircraft, modeling as most as dynamics of them, but nonlinear behaviors could not be considered on inversion dynamics [51] making this approach limited. Years later, for the tilting ro-

tors approach, small-size UAVs, it been developed a mechanism that could manage the rotation and vibrations due to rotors operation, implemented on a functional aircraft with two tilting rotors [32].

Other elements should be considered in those developments, this kind of configuration creates newer slopes of control, were necessary controllers to absorb the dynamics [31], and consider approaches for nonlinear behaviors [48], developments in the early 2000s, had limitations, from mechanism to processing fields, becoming into non-civil research, most of the prototypes develop were made by big aircraft companies, as Airbus, Boeing, Bell, and others [25].

In the second decade of the 20s, it started development of convertible configurations due to technology advance, implementing some controls and mathematical tools, to have a better performance on those systems that has uncertainty, the conversion phase is one of the troublesome cases, that switching process creates uncontrollable dynamics for both of the control schemes, preceding and incoming controllers are not designed to carry out that dynamic; some author use gain changing scheme to avoid those dynamics, but also considering some other elements as damping effects form real environmental, avoiding some uncertainties with that added schemes [18]; following years it was proposed some controller laws in order to create a robust system and mitigate those uncertainties, this paradigm allows to flight this kind of aircraft and control them with nonprofessional flight controllers, becoming into research platforms [57] those advance allow newer research to test and implement some dynamics on this aircraft, becoming into a research interest for lots of people [44].

Other investigations were focused on mechanism and wing interaction, giving valuable information for altitude and mission interactions with those dynamics [64] [58]. It is important to mention that this kind of configuration started in the 70s [33], especially for military applications and confidential research, but for civil, hobbyist and researchers 2010s become into the decade of the begging of important research.

It introduces some different configurations of convertible UAVs, from conventional ones [15], using quadrotors configurations with added components, or fixed-wing structure based [46], also more exotic configuration was introduced. Tricopter become into a newer and interesting configuration, where tilting mechanism become into a solution for it torque stabilization, as well as being a structure that could attach accessories or been modified for wing-based structure [8], [21], [48], [47].

Tilting rotor configuration becomes of the main studies of convertible UAVs, especially for its mechanism that was not already analyzed, where some authors focused on this field [63], and proposes were remarked for this experimental configuration [55], allowing the dynamics experimentation with controlled conditions as well as degrees of freedom limited.

In control, model, and mathematical fields it was focused on those configurations, especially at transitions and tilting mechanism representation [63], [53], [40], [8], [26] [30]. This configuration started its research with a better endurance hypothesis, especially for medium / long missions [20], but at its development, it arises other fields that become important, those are newer missions allowance, introducing more possibilities to the UAVs field [25], especially those that have a fixed-wing requirement for long packed delivery [17], or techniques that need more flexible aircraft [3]; at mechatronics field this aircraft also introduce more flexibility to avionics and sensors field, creating aircraft that could carry sensors that need to have hover flight but in remote spaces, or also low-speed flight with nonrelative angle [15]. All those points are key factors to select the studies of convertible aircraft, especially the design of one of them.

1.2 Justification

Unnamed Aerial Vehicles, commonly known as drones, are defined as powered aerial vehicles that do not carry a human operator, use aerodynamic forces, can fly autonomously or be piloted remotely, and can carry a payload according to the USA Department of Defense (DoD) [54], those characteristics become into a great research field due to its versatile and variety of applications from civil to military ones [9], that demand aircraft for specific applications, our research domain consider those that involves high precision, medium/long range and straight level flights.

Every mission considers different variables, and for that reason, a unique aircraft could not be used for all of them, but in terms of flexibility we design to accomplish as most as possible; nowadays multi-rotor aircraft are used for most civil missions and those that could not afford an expensive one, that aspects make some limitations on reaching complex missions.

Limitations are established by range, which is given by the battery and rotors, problematic for multi-rotor configurations. On the other hand, there is the fixed-wing aircraft which uses the forward aircraft airspeed and shape of the wing to perform its flight, in terms of power consumption this is more efficient, but some maneuvers cannot be performed especially those related to closed spaces.

Considering rotatory and fixed-wing aspects inspire us to create a hybrid aircraft where both of those configurations could work together to perform missions on multiple applications, the ones for our objectives are high precision agriculture, photometer study, package delivery, and active actuators implementations, where all of them is necessary precise flight with close maneuvers as well as long range. [48], [21], [10], [61], [4], [11] [62], [25].

In this research we present a novel design of UAV that gathers the capacities of rotatory and fixed wing, with a configuration of tricopter, it is attached a fixed wing as the main structure, and three groups of rotors which has the capability of tilting

movement, this at the same axis, allowing a thrust with variable direction. Those nonconventional configurations were evaluated as separate prototypes to adjust their dynamics but also to consider more than one prototype in this work.

The configuration proposed is considered a hybrid UAV, some authors named them as convertible ones [55], for practical terms both of them are correct, considering that we use the hybrid term for the perspective that in every moment the aircraft could use all the actuators without dependence on any establish configuration, for efficiency at high-speed flight it appears to disable the back-end group but in terms of functionality is always enable without delay for actuation.

This hybrid configuration with over-actuated outputs allows to have multiple configurations for maneuvers but also in terms of efficiency offers a better performance per watt used [20], at hovering it allows to have same thrust output for multiple actions thanks to its tilting capabilities, this behavior allows to have rotors at cruise speed which is more efficient than a changing rotor output. For cruise flight, it could be used as a fixed-wing aircraft with dual motor for power delivery, and control with differential forces on it, then for normal environments, but in case of challenging ones, it could firm up the control output with the other group of rotors, all of those options are the ones considered for the mixing matrix.

At this point, with all those recursive outputs, we could warranty another property for this aircraft which is output redundancy, in case of an error or accident it could continue its flight without some parts, for example, a rotor, or an actuator, part of the wing, a propeller, etc.

A newer implementation is challenging, some limitations are few data, non-direct reference and misunderstandings in the interpretation of results [11], at this case, there are other aircraft with similar implementations, but not exact models, in this case there is propose a novel implementation with a unique configuration, which create new behaviors and variables that are not considered at conventional configurations, our prototypes are fully implemented and design by our team, which consider me-

chanical design, mathematical modeling, flight computer implementation and sensors adequacy, that methodology allow us to have access to every variable of the system. On the other hand, we also require to consider every aspect to make the system works, and guarantee the operation of components, especially the flight computer and the sensors, for that reason, it was implemented at a quadcopter, demonstrating that this avionics configuration allows us to have an aircraft with correct capabilities to perform on normal conditions.

Other difficulties were adapting our designs to existing components, which have some sizing and in this case, some mass that change the whole configuration, where the rotors become a problem, giving less thrust than expected and concentrating the mass at the furthest points of the aircraft which change dynamics, parameters that forced us to perform more iterations before reaching a functional prototype, giving us the task of researching and implementing more resistant but at the same time lightweight materials to compensate for the aforementioned aspects.

This whole research is made to accomplish a hybrid mission the straight level flight with a self-sustaining UAV at cruise flight without sacrificing the hover capabilities of multi-rotors, which would allow an efficient mission with hybrid steps where a stable and straight route is mandatory, medical, photometer and surveillance applications demand those aspects.

1.3 Hypothesis

Hypothesis 1:The Tricopter with a fixed-wing structure has the possibility of two states of operation, hover, and cruise flight with pitch-less maneuvers.
Hypothesis 2: The convertible aircraft has the capabilities of hover flight with missions at low speed and close maneuvers.
Hypothesis 3: The UAV is capable of cruise flight at high speed for medium-range missions.
Hypothesis 4: Transition of flight states is possible by the aircraft.

1.4 The Research Domain

General Context: Design of convertible UAV with hover and cruise flight capabilities

Specific Context: Implementation of over-actuated UAV hybrid configuration with tilting rotors, fixed-wing body and tricopter configuration.

1.4.1 General objectives

Design and develop a convertible UAV prototype with hovering and high-speed cruise flight with auto sustainability capabilities.

1.4.2 Specific objectives

- Conceptual design of prototypes.

- Establish a flexible control model for tilting rotor aircraft with real implementation capacity in microcontrollers.
- Develop and implementation of prototype 0: test platform based on quadcopter configuration for avionics test.
- Development of prototype 1: Tilting rotor design for thrust with variable direction analysis.
- Growth of prototype 2: Weight optimization and free flight test.
- Propose a conceptual design for a partial auto sustentation aircraft.
- Full prototype development: implement fixed wing and rotatory wings design at the scaled structure.
- Prototype validation.
- Real-time experiments for each flight phase.
- Proposal of missions for convertible approach.

Chapter 2

Theory of Convertible UAVs

2.1 UAV's Types

Unnamed Aerial Vehicles (UAVs) are types of aircraft for specifics missions. That could be autonomous or piloted by a human operator at a ground station. Those aircraft could variate in some aspects, those used for classifications purpose are applications, flight conditions, maneuvers, sizing, propulsion, wing use, for general purpose it is important to recognize the limitations of each kind of UAV, and for this specific research, the approach to which it is related, especially between conventional and unconventional configurations.

2.1.1 UAV's Classification

As mentioned in the previous section, there are diverse types of aircraft classification, for this research, there is use three types of them, flight conditions, configuration, and wing use, also a combination of them are included; the aircraft described in this work is included in those classifications for the explanation proposes.

2.1.1.1 UAV's Flight Conditions Classifications

There are a large number of different kinds of aircraft, in the specific field of UAVs are reduced but still have a huge quantity, using the proposed classification in the "Handbook of UAV" [62], metrics used for that are mean takeoff weight, size, capabilities, operating conditions, and the combination of those characteristics [62].
It is important to mention that [62] classification considers just conventional aircraft which are designed for a specific application and delimited characteristics; this classification is presented in Table 2.1 for the existing system [11].
The categorization of Table 2.1 is based on characteristics referred to the flight of aircraft regardless of its execution, so it is a conceptualization of aircraft in general. In this case, it allows us to recognize aspects that are important for missions and used for parameter selections and effective load.
The aircraft contemplated is addressed at the "Micro" classification, especially for its mass and endurance, which is limited by the dimensions expected.

Type of UAV	Mass (kg)	Range (km)	Flight alt (m)	Endurance (h)
Micro	<5	<10	250	1
Mini	<20/25 30/ 150	<10	150/250/ 300	<2
Close range (CR)	25-150	10-30	3000	2-4
Short range (SR)	50-250	30-70	3000	3-6
Medium range (MR)	150-500	70-200	5000	6-10
MR endurance (MRE)	500-1500	>500	8000	10-18
Low altitude, deep penetration (LADP)	250-2500	>250	50-9000	0.5-1
Low altitude, long endurance (LALE)	15-25	>500	3000	>24
Medium altitude, long endurance (MALE)	1000-1500	>500	3000	24-48
High altitude, long endurance (HALE)	2500-5000	>2000	20000	24-48

Table 2.1: UAV categorization for general purpose UAVs [11].

2.1.1.2 UAV's Configuration Classifications

A general classification based on the lift principle allows us to separate the type of aircraft based on its wings, commonly this classification gave us two kinds of aircraft, those based on fixed-wing (FW) and rotatory (RW) ones, but lately, there is include a newer classification, those based on a hybrid approach where both ones induce lift force [20].

Lift force is provided by aerodynamics, especially airfoils, which depend on the nature of the wings, for fixed wings, this force is induced by air interaction with the

wing, as seen in Figure 2.1 wherein the (a) section could appreciate the nature of air attack on the aircraft, and section (b) is an example of this kind of aircraft.

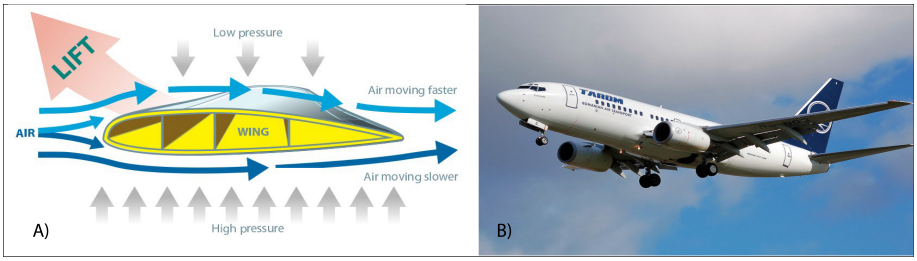


Figure 2.1: Fixed Wing principles, a) Lift principle for fixed wing geometry, b) Fixed wing aircraft example.

For rotatory wings, lift is provided by the axes of springs, causing the lift forces due to the cutting action of air from the shape of blades, this kind of configuration allows hover capabilities,without using on runways, but with less range than FW. In multirotors configurations there are more maneuverability and superior hover capabilities, as seen in Figure 2.2, where in section a) is shown the principle described previously, and also in section b), there is an example of rotatory wing aircraft, and in section c), a multi-rotor one.

Figure 2.2: Rotatory-Wing principles, a) Rotatory Wing principle , b) Rotatory wing aircraft example, C) Multirotor configuration.

Depending on the application, each of those groups has advantages, the fixed wing can carry bigger payloads and has more range per fuel consumption, but rotatory wings have an important advantage, vertical take-off and landing, which allow

the aircraft to perform a greater variety of missions and operate in narrower locations [24]. Those advantage inspires the community to unify them into one group that could take advantage of both configurations creating hybrid approaches, where depending on design parameters, a single aircraft uses a fixed wing for cruise flight and a rotatory wing for the hover state.

Hybrid approaches have a wide variety of aircraft; those depend on actuators combinations, and also on the dependence of configurations. Most common is dependence on tilting rotors for stable cruise flight, which is not capable of staying at that condition with just fixedwing, but those combinations allow the aircraft to have another dynamics, which improve mission accomplishment and also flexibility in navigation, especially in free spaces.

The more iconic configuration used by the U.S. Army of Hybrid is the V-22 Osprey, the direct inspiration for this research, is a VTOL but also could use cruise flight for medium and long-range missions, as seen in Figure 2.3, this aircraft use its tilting rotors for directional thrust and also vertical and horizontal stabilizers for control at high-speed flights, in this case, those for cruise one, another advantage of this design is the payload capacity, been a cargo aircraft, allowing to transport of big packages or lots of crew for missions.

Figure 2.3: Hybrid Aircraft V-22 Osprey, with tilting rotors and full convertible capabilities.

2.1.1.3 Multirotors

A multirotor aircraft is defined as an aerial vehicle that has multiple rotors which are used for propulsion and control [41], that kind of aircraft is usually small and lightweight, used for surveillance, reconnaissance, mapping, cartography, border patrol, inspection, homeland security, search and rescue, fire detection, agricultural imaging, traffic monitoring and others [12].

The quadcopter is the most used configuration of multi-rotor unmanned air vehicle (MUAV), due to its versatility, absence of tilting mechanisms, and high maneuverability [50].

On multi-rotors, it is important to consider degrees of freedom that need to be satisfied with the motors or being delimiter by the control paradigm, some approaches to perform that are limiting angles, narrowing down the system. Most of these systems are powered by electrical approaches, but there is also fuel power, which is not a common configuration thanks to its transition behavior, as mentioned before, its main source of the thrust is rotatory wing, commonly known as propellers, which are attached to each motor, using those principles, an aircraft of multi-rotor could perform a flight.

That kind of aircraft has the advantage of being able to perform a close flight, hover, and precise navigation [50] [41] [11]. However on the other hand, it lacks medium and long range, high-speed cruise and efficiency, and it could carry small payloads against its size.[62]

2.1.1.4 Fixed Wing

This configuration uses the interaction of wing and airspeed, performing a lift force that induces flight conditions, based on wing shape and its wind directions, it is developed that forces. There are also other forces, such as drag, disturbances, and

others, that also interact. However, for simplifications in this research, there are considered just those that are involved at the wing, making an exclusion on fuselage, accessories, and other elements that are not carried at our design.

In propulsion subject, there are different fields, where fixed-wing-based aircraft usually use motors, turbo-props, turbines, or other approaches depending on the service developed by the aircraft, that are used just for thrust purposes at single input devices, and in some specifics maneuvers, differential propulsion is used by a dual or a symmetrical number of inputs of thrust [11].

For control maneuvers, there are necessary actuators to have inputs related to aircraft; control surfaces are used for that sense too. Those are based on aerodynamics where a different distribution of lift force creates different vector directions that are interpreted as navigation control variances [11].

This type of aircraft is highly used for cargo and long-range missions, its efficiency, and fail-safe models allow them to use in a wide range of applications [11], but there are also disadvantages, the most remarkable are the dependence on runways, also its characteristics are limited by wing design,which is necessary for some cruise flight speeds to be efficient, as well as a lack of hover and close maneuvers where the lift is compromised if there is no wind speed.

2.1.2 Convertible aircraft

There has been growing interest in UAVs with hybrid capacities, with a lead on improvements and flexibility for a broader range of missions. Those requirements develop the term convertible UAV, which could manage multiple states for divergent phases or different missions [9]. As the main concept describes, there are different kinds of aircraft for different missions, but also different configurations could perform the same missions, which extend this kind of configuration of convertible UAVs into an extensive classification. For that reason, this research is bounded to convertible UAVs that involves a change of lift force dependence, specifically from rotatory wings

to fixed-wing thrust direction would be considered on them.

It is important to mention that a convertible approach is not only an aircraft with multiple kinds of actuators or multiple phases. Convertible UAVs involves new dynamics and new kind of approaches to control them; with those new parameters are perform missions and schemes in such way that the system is different to normal configuration, normally there are use for performance and power efficiency, adding capabilities to maneuver in a more aggressive way, or develop maneuvers with actuators that need less energy to work; It is clear that when making a change in the scheme, other parameters are changed, in some cases stability is compromised or new dynamics are added which need to be mitigated.

Some authors use this kind of configuration for improvements in stability and capabilities [9], [20], [24], but some others use it for under-actuated systems that are not naturally stable [30], [26], [55], [29], been this configuration a method to develop newer configurations that are not commonly used.

2.1.2.1 Types of Convertibles UAVs

Most convertible UAVs could integrate a convertible configuration, where the mission to accomplish is the delimitation to perform the design. Table 2.2 establishes some common types, and in this case, the reference used for our design could be integrated into one configuration for some required dynamics. Other aspects to consider for convertible UAVs are that those configurations are delimited by application and size requirements, considering the "Micro" configuration, presented in Table 2.1 for this section, as the delimiter to reduce studied options.

Type of Convertible UAV	Description
Tilting Rotors	Its main objective is to use as less as possible rotors speed change holding them in the same range just modifying their direction with external actuators that could variate the angle of the hole rotor and its propeller.
Lift transition	This configuration is based on multiple lift generators attached to same structure, normally compound by a combination of fixed-wing and rotatory wings, using them at different phases.
Directional Propulsion	Normally the propulsion sector is based on turbines attached to the main body which has a variable output of exhaust gases, that variation in direction create a changing vector used for control and efficiency, at small applications, it is presented at ducted fans configurations.

Table 2.2: Type of Convertible UAVs.

This classification is important for conventional and unconventional design; most authors use one of them to simplify dynamics description and produce just the actuators that need it to accomplish the degrees of freedom, for stability purposes [53], [41].

A configuration with multiple convertible types could perform more efficiently [20] and maneuvers [24], making these novel configurations into research interest.

Convertible UAVs are used especially for recognition and agricultural missions [60], [30], where their mission of high speed but also phases of hover are accomplished by this aircraft, further involving efficiency.

The first convertible approaches came from French approaches with tilt rotors, creating a patent for that mechanism; other Americans also considered VTOL configuration in 1930. However, at that time, it was not possible to develop a project

with that characteristics. At this time, miniaturization was not possible, technology did not allow to perform small models, due to extensive electronics systems, so at the beginnings of convertible aircraft, just macro structures were allowed. In that sense, it developed military aircraft with the main objective of VTOL capabilities, a timeline could be established as mentioned in the list below [25].

- Lockheed XFV-1: first convertible aircraft reported with successful flights and transitions. It was based on tail sitter configuration with the low-speed transition of phases; it could perform its VTOL objective.
- Hawker P1127/Harrier: First jet aircraft with VTOL capacity, created for Royal Air Force, nonagile maneuvers, its time of service of more than 50 years, the feasibility of convertible aircraft is approved.
- Bell X-22: First tilted rotors functional prototype; total dependence on that system makes them crash.
- Bell-Boeing V-22: One of the few convertible aircraft approved for serial production, newer slopes introduced, reported being expensive in support, maintenance, and slow transition maneuvers.
- F35-B SVTOL: VTOL capabilities on existing aircraft, as an adaptation it lacks the system-reducing capabilities, it performed slowly an inefficiently, designed for hard landings as carriers to land bases missions.
- WingtraOne: Reliable aircraft of small factor, fully autonomous for take-off, transition, and landing, completed high-precision missions, feasibility on small aircraft is accomplished.

2.2 Aerodynamics Effects

In convertible aircraft, multiple aerodynamics are involved, principal interaction are in rotors with tilting action, there are huge quantities of considerations, to mention one of them, it is the angle of attack of each plate, it change with the tilting action, which evoke aerodynamics effects; it depend on the system, that could be used or be a perturbation. For this research, the effects are listed below:

- Forces interactions from the rotatory and fixed-wing.
- Effects of the angle of attack for the tilted rotor.
- Interaction between the vortex of the rotatory wing and fixed wing.
- Damping effect by fixed wing.
- Transition disturbances.

This section would be used as a summary of those aerodynamic effects. No in-depth investigation is sought, just an explanation of those aerodynamic elements that would affect the final prototype.
It mentioned forces interactions, angle of attack, and transition disturbances. First two terms are mentioned as summarize and definition of effects that interact with our convertible approach.However, the section that is directly related to this investigation is the one on transition, which is unique for this kind of configuration, been important at the design of aircraft, for flight planning and control consideration; at both cases it is important to identify those dynamics that interact with our aircraft, to compensate them or use them for our propose.

2.2.1 Forces interactions

On convertible UAVs, interactions between the combinations of rotors, actuators, and surfaces are added to the system. Also, their positioning of them affects their interactions. In the aerodynamics field, those aspects involve system alteration due to induced wind; the most common are rotor wake to fixed wing [39], as seen in Figure 2.4, which creates a vortex interaction between wind due to linear displacement and rotor wake into the fixed wing. Those aspects reduce the wing efficiency, the effective area, and the direct relation with fewer lift forces [66]; at tilting rotors, there are other aspects to consider, where rotor wakes direction is different at each angle, inducing flow with a different direction.

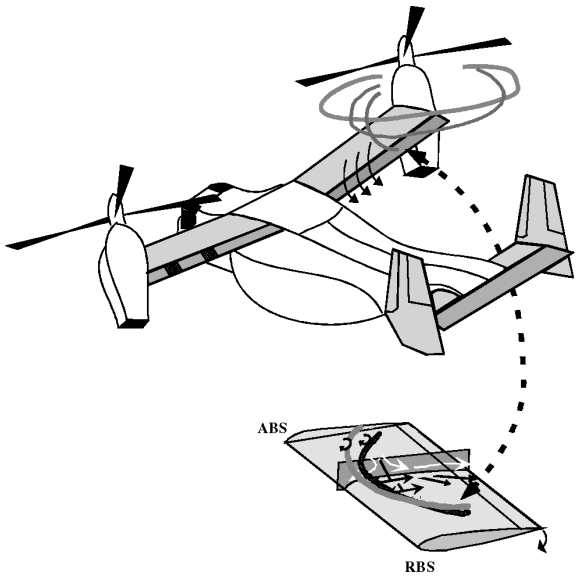


Figure 2.4: Wind flow interaction between rotors and Fixed Wing, image from [39].

As seen in Figure 2.4, it is important to reduce the area where the rotor disc is directly spanning the wing area. For our approach, rotors are outside the wing area; just the external vortex could react with the wing tip vortex, which is not a completely bad effect. This interaction also affects the positive to the wing due to vortex redirection, becoming a wing tip [65]. However, for this investigation, it would not be depth investigated, just mentioned as aerodynamic effect on this geometry.

2.2.2 Angle of attack

This aerodynamic effect is related to the wind flow on the airfoil, becoming a consideration for force generation and disturbances due to tilting, which changes the entire incidence of the system [6]. Angle of attack is a parameter which is critical on flying systems, especially in rotatory systems. This is the angle between the airfoil chord and its direction of motion relative to the air. For the rotatory system is the resultant relative wind, which changes due to pitch angle and external disturbances; this make a change on the angle of attack, due to that behavior; For tilting mechanics is also include that variable, where the angle of tilting also induce a change of the resultant angle, in Figure 2.5 is illustrated those interactions of angles with resultant one. For our purpose of investigation, these effects are related to the tilting angle, which affects our system due to the pitch-less objective. In that sense, angle and surfaces interactions is eliminated from effects to the fixed wing, just the environmental field would be consider. Other interactions between blades and wings will be studied in the future.

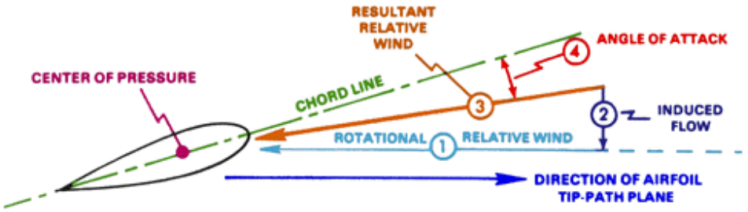


Figure 2.5: Angle of attack for wings, rotatory approach [16].

2.2.3 Transition Disturbances

There are unmodeled dynamics for non-conventional aircrafts; these include the interactions on actuators, especially in the aerodynamics field, where a change in structure, surface, or propulsion affects the system interaction in aerodynamics forces.

For the convertible approach, there is a crucial factor that affects the entire system, which is related to its natural behavior of flight phases. Each phase interacts with diverse kinds of forces affecting the system, as well as airspeed, maneuvers, and other elements. Using a convention of simplifying it could be considered as a multi-phase system, where this investigation would not consider the transition phase for characterization and control approaches, just a flexible application of it to absorb those effects; in the aerodynamics field, those transitions also induce some unexpected behaviors, especially if the system is considered an instantaneous change of phase, at this case, it has some phenoms as stall, propulsion loss, inconsistent height control, uncontrollable maneuvers, among others. [6]

Historically, Boeing V-22 is a convertible aircraft with promising flights and the example for designs and development in the research. This design can be extrapolated to other aircrafts. For example, rotor wake, that in this case has an interaction between its fixed wing and propulsion. In the transitions disturbance field, the V-22 shows some dynamics that are reproduced in other aircrafts, where transition time between phases is one of those dynamics that extrapolate to others aircrafts [28]. An important parameter is the stall delay, which is significant for phase change. It is important to mention that macro structures are limited by actuators, materials and safety operation, giving results of slow-outputs that are scaled to nonresponsive systems. In that sense, a small prototype achieves some dynamics and capabilities that cannot be developed in macro structures, due to limitations in the actuators. For example tilting mechanism for hover stabilization on V-22 aircraft, tilting mechanism on this aircraft is use just for flight phase development, not for active actuation.

Other effects due to tilting mechanics are related to resultant forces, which are mentioned below [6].

For tilting rotors towards airplane mode:

- The fuselage attitude opposed the rotor tilt and pitched more nose-up.
- The rotor thrust vector is re-orientated due to reactive pitching.

- It produces a large down-wash angle at the tailplane, reducing its lift and resulting in an increased nose-up.
- Rotors affect empennage wind interaction due to disturbances.

For rotors tilted with 45 deg:

- Fuselage pitch attitude was negligibly affected by interactions.
- Wing and empennage interactions are greater than disturbances by rotor wake.
- Reactive pitch due to rotors vector.

For rotors in helicopter mode:

- Pitch trimmed by the influence of nose-down.
- Lift is entirely influenced by rotors lift.
- Nonfixed tilting rotors maneuvers are achieved for hover flight.
- Low forward speeds are developed.

For this tilting rotor configuration, it is a predominance of pitching behaviors due to its tilting direction, which is aligned; this investigation approach considers that behavior and its influence by them to propose a pitch-less flight. For that reason, it was necessary to recognize those dynamics related to aerodynamics for this configuration, relying on literature and selecting a similar configuration for it, V-22.

Chapter 3

Design Proposal

UAVs design involves some different methodologies, that depends on configuration, avionics to use and the mission expected, is important to establish a methodology to use for the design of the aircraft, whereas conventional configuration as quadrotor are focused on rigid structures, an efficient combination of rotors and propellers and endurance [12], [11], [62]. Due to its configuration, some aspects such as fuselage are not carried out as primary objectives, those are established after the conceptual design is performed. But on the other hand, there are unconventional configurations, such as convertible approaches, that are focused on their dynamics, becoming a hard-working processes, from selecting their objectives to manufacturing.

Convertible configurations are limited by actuators and materials, for that reason some authors propose a methodology to perform this process [48], [61], [52]; nevertheless, there is not a realistic approach that established a flexible methodology, which is based on its specific configuration, for that reason at this investigation it is proposed a methodology that allows us to validate sections of the design isolated and then collected for the final prototype.

Our methodology includes aspects to validate parts of the aircraft from avionics to aerodynamics, those elements are enlisted below:

- To establish the main structure of the prototype.

- To design and validate a known UAV configuration (quadrotor).
- To validate the avionics on conventional configuration.
- Dynamics select for convertible configuration.
- To validate mechanisms and actuators established for dynamics sought.
- To design the fixed-wing.
- To collect elements on the final prototype.
- To validate the prototype.

To accomplish the objectives of the proposed methodology, it is necessary the fulfillment of 3 prototypes; the first one is related to a conventional configuration, known as a quadrotor which is selected for this objective and designed as an experimental platform for dynamics and avionics validations. Once the system is ready to perform missions without drawbacks it would be implemented on a second prototype, which includes more actuators that represent tilting capabilities and tricopter configuration. This system is used for testing and validations of dynamics, establishing times, components limitations, and propeller performance on a different angle of incidence. As the third and final prototype a collected system is performed with a fixed-wing structure, this has all the capabilities and acceptable performance, with hover and cruise flight capabilities. A design proposal for those configurations is presented in the sections below.

3.1 Quadrotor

A quadrotor is a type of aircraft based on 4 rotors, used for propulsion and control, the dependence of 4 actuators for 6 degrees of freedom (DoF) makes an unstable system but for limited angles, it could be considered stable. The quadrotor is one of the most common configurations of small aircraft due to its versatility and flexibility

for outdoor and indoor missions. In this case, an aircraft design is proposed, to evaluate the dynamics, avionics, and limitations of the manufacturing process.

3.1.1 Design objectives

A small form factor quadrotor is expected as result, our parameters to design and delimiter are:

- Maximum diagonal on XY plane limited to 40cm.
- Micro configuration with civil allowance
- 249 grams as the maximum weight
- Must be full debug-gable
- Fast assemblage
- Flexible for prototyping
- Additive Manufacture Based
- Fast response

These parameters were selected to develop an experimental platform to have a flexible and trustworthy platform that could allow us to evaluate dynamics, and avionics and interconnect them with our actual approaches, also a future objective of this small platform is to evaluate swarm interactions, giving us interconnection control requirements.
For design purposes, components need to be selected before a structural design could be performed, our methodology is based on computer-propulsion-manufacture selection, in the following sections, it is developing this methodology.

3.1.1.1 Flight Controller Computer

A flight controller computer at aircraft design implied a combination of microcontroller, sensors, protocols, and power units, all embedded into a system, depending on the application some redundancy is expected.
Depending on the kind and number of actuators some controllers would be incompatible, these requirements establish some limitations on commercial flight controllers, for example, the Pixhawk unit, and others, are designed for some specific configurations, especially quadrotor, Hexarotor and octorotor, limited by its internal software as well output section, that is designed for commercial accessories and actuators.
In the prototyping and developing stage is necessary to have an open-source platform to control each parameter of the aircraft, avoiding uncertainty and incompatibility; this research is establishing a complete flight controller; develop and create by our internal team, our objective is to guarantee that every variable would be designed and known, this to have the capability of system debugging, which allow us to inspect and command all control stages.
The requirements established for the flight controller of this system were:

- ARM base micro-controller ESP32 Dev Module
- 32-bits based architecture
- Dual-core
- 500Hz frequency
- Multitasking handle
- Telemetry capabilities, IoT protocols desirable
- Double precision processing
- 16 bits outputs
- I2C, SPI, and UART protocols compatibility

- Inertial Motion Unit (IMU)
- 5V and 3.3V power unit
- Interchangeable boards

Our development uses an ARM Cortex M0 micro-controller that allows us to have all the characteristics mentioned before, as seen in Figure 3.1, it also embeds an MPU9250 to have de IMU capabilities, this configuration allows us to program our code with the whole control of the system re-queried for the developing stage, additionally, WIFI is selected for telemetry purposes by the UDP protocol, performing a low latency communication and scalable capability.

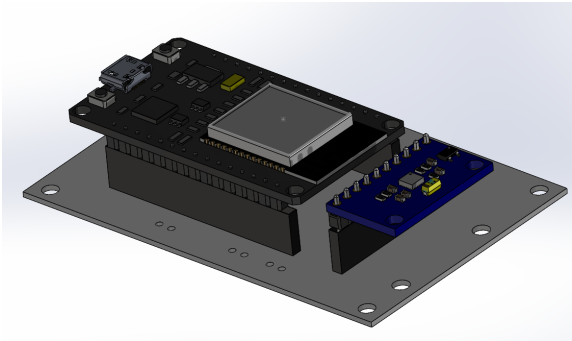


Figure 3.1: Flight Controller Computer based on ARM cortex M0 architecture, with sensors and outputs embed.

For better performance, all the programs were developed in C++ and used without library references, just the one used by the microcontroller for the interpretation of defined variables and language particularities.

3.1.1.2 Propulsion

It is known that propulsion selection is one of the most important parts of an aircraft design, this provides the performance of the system, UAVs a fast transient,

stable actuators, and high-resolution systems that allow good performance for precision maneuver, furthermore those systems are designed with some physical aspect as consideration.

In the UAV fields are highly use propellers and electric ducted fans (EDF), in most civil applications propellers are predominant; twist angle and radius are the parameters to consider for geometrical design additionally arm interactions or fuselage are considered at aerodynamics analysis becoming the initial parameters to design as dimension limitations.

Is important to recognize the relation between rotors and propellers, chiefly the charge factor, a rotor is designed for maximum resistance to movements, if it is exceeded it will burn internal parts of the motor, coils, due to the over-current demanded by the motor, for this consideration there is propellers recommendation by the manufacturer, for practical use we are limited to them, considering just the combination of the number of blades and maximum rotor speed.

Small motors are mostly rotors of high KV (Relation between voltage and rotors speed) due to battery limitations, especially battery cells, giving the requirement for a system of 1 or 2 cells, is in the range of 3.7 to 7.4V, for that reason it must perform this consideration, computing the relation KV and having small propellers it must accomplish a high rotatory speed to be able of a highly responsive and stable system.

Using the maximum diagonal, Flight Controller Computer dimensions were selected for propellers.

- Propeller 1: 65mm of radius, the twist angle of X, Tri-blade
- Propeller 2: 80mm of radius, the twist angle of X, Bi-blade

Both configurations are accepted by rotors, in this case, it is selected the one that has less aerodynamic interaction with arms and UAVs body, in Figure 3.2 is illustrated these relations.

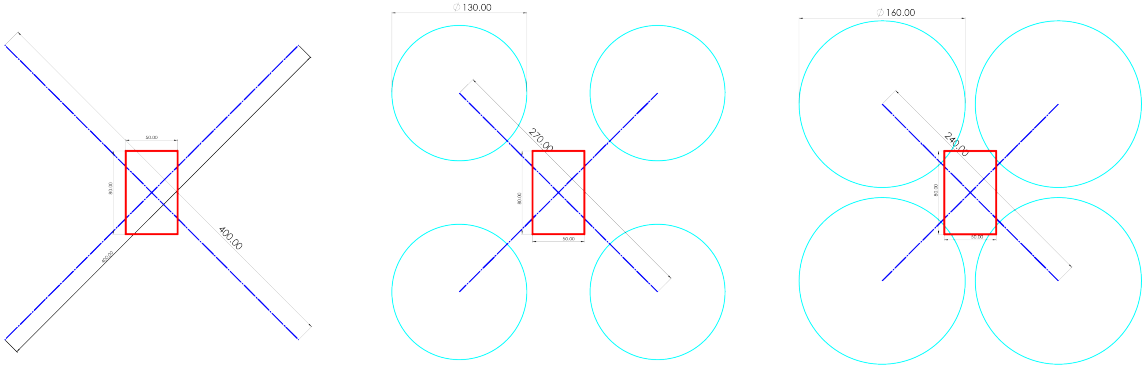


Figure 3.2: Selection diagram for propeller selection based on maximum dimension accomplish.

Is important that the first diagram of Figure 3.2 is the reference plane, where blue lines are used for maximum diagonal, red lines for Flight Controller Computer (FCC) dimensions, and sky-blue for area use for blades movement, second diagram illustrated the interaction of the system with 65mm blades giving us enough space for FCC isolation, the third diagram shows the system with 80mm blades, they are adjusted enough to fit this system but the avionics system would be compromise, also the vortex interaction between propellers and fuselage is harder[59]; to avoid problems some accessories must be implemented, for this light-weight system this discard this option, selection of 65mm blades is mandatory for better interaction.

3.1.1.3 Manufacture Planning

A prototype model is expected, for that reason, a manufacturing process that allows us to make iterations of the same model and same time use engineering materials is Additive Manufacture (AM), for UAVs it commonly uses polymer materials [40], narrows down AM technologies to Fused Deposit Material (FMD), and Stereolithography (SLA), both technologies accept polymer materials, for flexibility and cost FDM is selected to prototype and manufacture these models, expecting acceptable physics resistance.

One of this prototype objectives is to have a reduced dimension UAV, in Figure 3.3 are shown max dimension that is required.

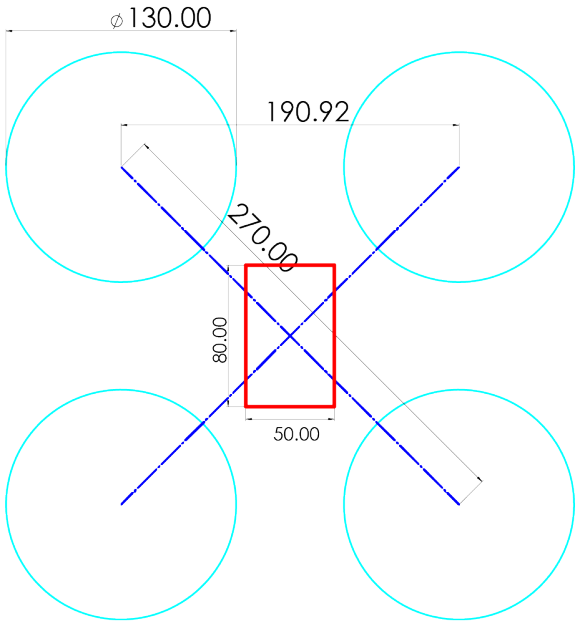


Figure 3.3: Diagram for maximum dimension expected for Quadrotor aircraft at XY plane.

The maximum diagonal allowed is 400mm, and the diameter of propellers is 130mm, giving us 140mm of diagonal for FCC and accessories, this is our effective area, but there is some consideration.

The first consideration is that this system is a multidimensional object, that allows us to have a sandwich configuration, perfect for fast prototyping as well as for flexible at updates; other considerations are related to max XY printing zone, due to AM parameters, the specific parameter of every 3D printer, at this case, it is used 210x210 mm of workbench for XY plane, this gives us diagonal of 270mm and 190.92 mm for every hick, equal at this case for square configuration, this consideration is part of manufacture planning, where is select the planes of printing, considering delimitation plane to avoid fractures induce by actuator forces.

The methodology used for this prototype in AM field is based on characteristics that could be developed by AM Table 3.1 are explained what is used for this case,

considering aspects that are important to ensure the correct manufacture of this model as well as developing the parameters expected for resistance of this prototype. Another aspect to consider in this research is modularity, becoming an important aspect, especially for the nature of this research, since the parameters and capacities will be related to the other two developments mentioned in this work, those aspects are important if we consider this as part of design methodology, where the material, accessories a flight controller would be tested at a known aircraft expecting some results, this is important if we consider the whole system a complex system that is important to reduce to appreciate those aspects due to each configuration.

Characteristic	Description
Material	A prototype is strong as its material selected, this section should be analyzed according to forces and dynamics that are involved in the model.
Sizing	Every kind of printer has its limitations, is important to recognize which are the ones involved with the process, the ones used for this kind of prototype are the smallest parts that could be processed as well as resistance compromise dependence on geometry.
Bridges and specials geometries	One of the most important capabilities is to know which shapes can be printed, this type of manufacturing allows to develop of parts with internal geometries, as well as ducts giving the embed possibility.
Interface	In the case of post-assembly, it is required a method for adhesion, mechanical or glue based, is important to define these in order to generate a precise part.

Table 3.1: Considerations for additive manufacture prototype.

Our major force to analyze and redirect throw the structure is the one produced by motors, which are aligned with the Z axis and react on torsional effort

in the rotation direction, with this consideration it could establish AM planes and assembly methods, where glue-based interfaces do not allow to have de modularity and reparability capabilities and the principal plane will be perpendicular to the directions of the principal forces.

Considerations presented in Table 3.1 are related to the dimensional and capabilities of specific machines, for this case consider conventional machines with Cartesian XYZ configurations and 210x210x250 mm printing volume, such as Ender 3, Anet A8, Anycubic Viper, etc.
The last parameter to drawing and designing our prototype is to recognize the limitations and techniques required for our options selected for this research, where a correct AM design process and avionics integration would be reflected in the desired results.

3.1.2 Structure

This quadrotor is based on an X configuration with equal dimensions between arms and filled with a slab which is used as support for avionics elements, and also to create a closed loop at the structure to reduce XY deflections.
Layer design is also proposed to create a modular design, where each layer could be filled with power modules, avionics, or accessories, this making reference to a sandwich configuration, ideal for prototyping, but also as a test basis, that allows the research group to taste different configuration, signal processing, and UAVs swarms, this allow by the possibility of creating and debugging each layer of control.
The base model would be designed as 2 layer configuration where the first layer is based on the main body with motor attachment, principal avionics integration, and main ESC controllers; the second layer is the desire for a power module and landing gear attachment, making a design that situates the center of mass into the center of structure, this to have a system with equal dynamics into all axis.

3.1.2.1 Main Body Layer

As the principal structure of this aircraft, this corresponds to the first layer of the aircraft, which is important to have a rigid and stable structure, methodology proposed for this design is the one presented below:

1. Identify principal points of structure (where forces are applied and avionics attachments).
2. Establish max dimensions and reduce overlapping between points selected.
3. Re-design for clearance between components.

Using the reduce methodology mentioned before, it is selected in Figure 3.4, section a), principal points, red dots for motor attachment, which are the point where is applied the forces, green rectangles for avionics area, and blue circles for blades effective area, at this case it where separate arbitrarily, on steps below would be dimensioned for that purpose; at section b) red line it is used as maximum diagonal allow by this design and blue line for the center of motor location, a simple subtraction between two times de propeller radius across max length it is used for this diagonal selection.

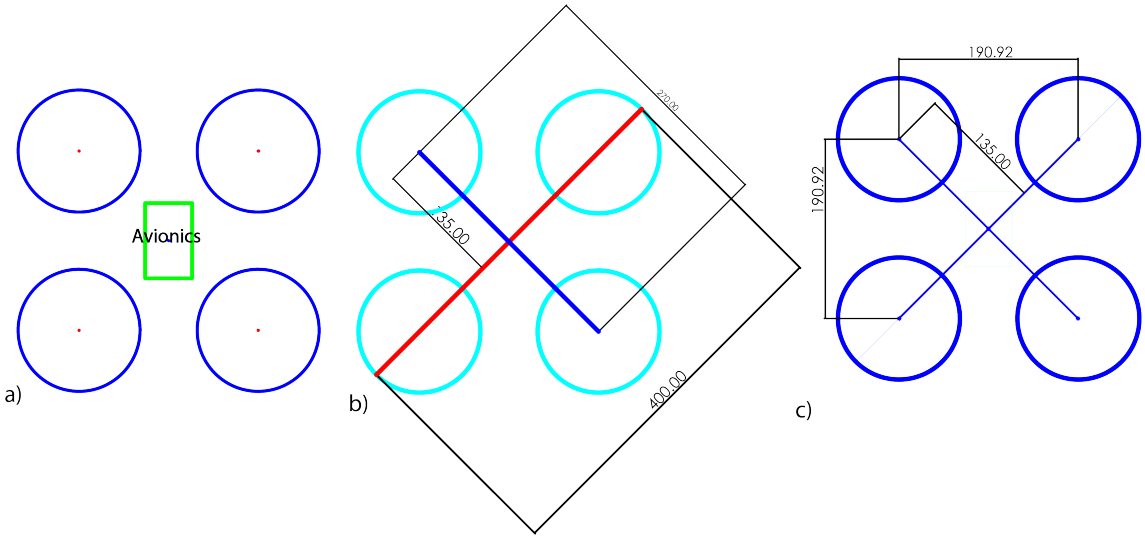


Figure 3.4: Quadrotor structural methodology, Section a) First draw, points of forces and effective areas placement, using "X" configuration, Section b) Draw dimensioned, Section c) Clarence configuration.

With those configurations a volumetric model could be a draw, aspects such as arm width were obtained based on motors dimensions, especially the area of contact with the aircraft, these considerations are applicable with most multi-rotors, giving us a structure strong enough for the stable flight using polymers, commonly acrylonitrile butadiene styrene (ABS).

For modular capabilities, it was decided to create removable parts, especially those that attach the motor with the structure, giving a more flexible assembly method as well as reparable capabilities, Figure 3.5 is shown this structure, which is also filled with a slap that connects the arms with the avionics spaces.

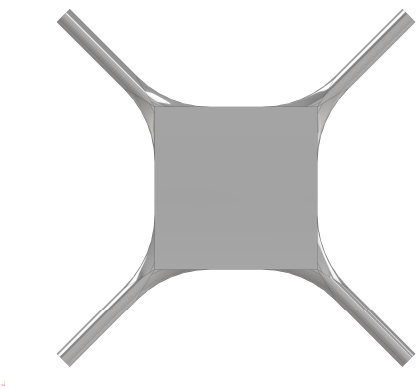


Figure 3.5: Volumetric design of quadrotor.

This structure has been topology optimized, getting as result Figure 3.6. This design it is use as final for this prototype with also the holes and attachment for final assembly.

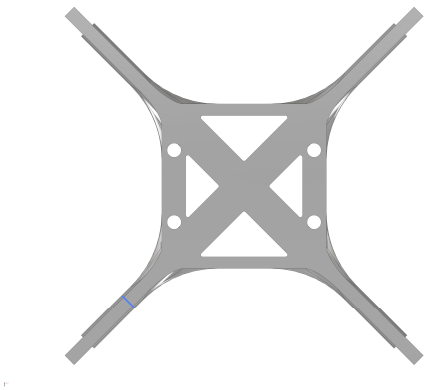


Figure 3.6: Final model of main body for Quadrotor prototype.

3.1.2.2 Power Module Layer

This design is based on layers, where each of them should be assembled with the main one shown in Figure 3.6, this is accomplished with the locations of assembly holes, which are designed to fit at every layer as well as be used with bolts and nuts,

with this configuration we could attach every layer and accessories, for this layer use the location plane shown in Figure 3.7, essential dimensions are presented, and the battery area is located, with these references a part is developed and optimized.

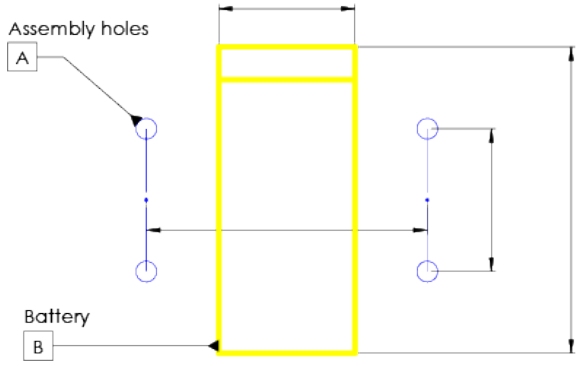


Figure 3.7: Location diagram for power module with essentials holes at reference A, and battery area at reference B with yellow lines

The part develops for this layer, is the one in Figure 3.8, which is reduced at its minimum mass design, and is only intended as support for battery placement and connection with the landing gear.

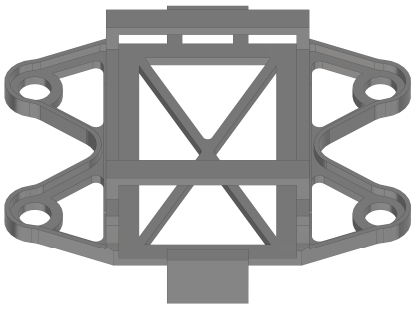


Figure 3.8: Part develop for power module layer with all of attachments for battery.

3.1.2.3 Layer assembly

The particularity of this design lies in its ability to be assembled by layers, which allows us to generate a flexible and expandable system, in Figure 3.9 this method is illustrated for the frontal plane, and a diagonal plane is presented in Figure 3.10, which capabilities of assembly were important for this modular design.

Figure 3.9: Frontal plane of quadrotor prototype at exploded view, highlighting the sandwich layer configuration.

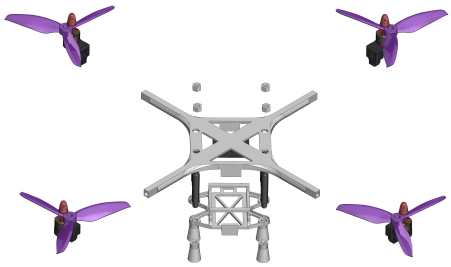


Figure 3.10: Diagonal plane of quadrotor prototype at exploded view.

This mechanical assembly is developed with bolts and nuts, ideal for fast assembly, where is only necessary to screw in these parts to create a quadrotor.

3.1.3 Manufacture

As the main manufacturing process additive manufacture was selected to create each part of this prototype, the reason for the flexible and fast prototyping process, where an upgrade could be performed at any moment.

All the prototypes were manufactured in a conventional Cartesian XYZ 3D printer, model Ender, thanks to its flexibility and unrestricted access to every parameter, which allows the creation of personalized parts, with unconventional parameters, trajectories, and material parameters.

Is important to mention that every model that is present in this research is intended and designed for AM, reducing supports, and increasing the directional behavior of AM parts, due to an-isotropic behavior, which depending on the context can be a good or bad parameter, it is intended a breakable part that dissipates energy at fatal cases, it is an expectation parameter to redirect and place this break-away plane to a direction desired.

For AM is necessary to follow some pre-requisite, that one involves processing the CAD part eliminating mesh errors, and also to resizing those structures that are not possible with the printer configuration, additionally a slicing process is required to convert solid parts into slices for a planar printer, which would be interpreted as G-Code, that is machine language.

The slicing process is perform at CURA software, which is Ultimaker software for printers that allow us to use those parameters need it for our printer as we as being advanced and flexible software giving the possibility of full parameters control, for illustrative purpose, is shown the main body of simulated the workbench at Figure 3.11, this kind of part is primitive, where is only necessary to place them into workbench and decide the plane for printing, at this case parallel to the part that allows us to have a strong part for our purposes, internal trajectories of printing and infill parameters were selected according to mass and sizing requirements, not critical for structural integrity.

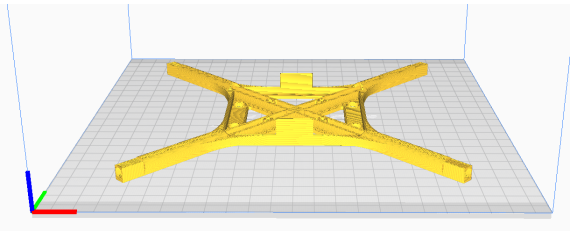


Figure 3.11: Representation of quadrotor prototype simulated for AM at CURA software.

As seen in Figure 3.9, this model is designed as a sandwich, giving us the potential for easy assembly, once is produce every part of this system is assembled in a couple of steps that are insignificant for this research, and a final prototype assemble is the one at Figure 3.12, for this project is named ”Benito” and for multiple iterations are named as elements, some VICON markers were attached for experiments that would test performance at validation section.

Figure 3.12: Experimental prototype of small quadrotor, project name "Benito".

3.2 Tilt-rotor

A tiltrotor is an aircraft that has at least one rotor attached to a mechanic that allows a change in direction of a propulsion system, to change the force component

regards the body frame; for conventional UAVs, this configuration allows to have a system with more actuators that are directly related to DoF but it adds a system that is no longer equal in terms of establishing time; tilting mechanism tends to be less responsive [9] [26], especially at big and sudden changes; on other hand, tilting mechanism allows newer dynamics that are used for mitigation of dynamics that are not possible to absorb with just throttle control, also deviation of the system could be mitigated with offsets of the mechanism, that modify the configuration at real-time, nevertheless, could be stored as initial configuration, this in the sense of accident and manufacture deviations.

Most of the configurations developed for other groups of investigation are based on conventional quadrotors on "X" configuration with tilted rotors, which accomplish the definition, but in this case, it is proposed a "T" configuration, usually use at trirotor configuration, but for this development is add an extra rotor for stabilizing and got more actuators to accomplish at least the same number of DoF with same actuators.

This prototype is challenging, this problem would be presented in the structure section, which is related to compact structures, due to the simplification of this prototype, is necessary to have a rigid structure made by a compact geometry, which creates a complex design, which can hold the forces of the rotors at larger arms.

3.2.1 Principles

This aircraft is designed to study tilting rotor configuration and applied them in this prototype as well as in the final prototype of this research.

Torque establish is used as a quadrotor configuration, where there are 2 frontal rotors (A & B Markers), both have tilting capabilities, and 2 rotors at the tail (C Marker), these are static and with the opposite direction, with those 4 rotors the torque is canceled having the same output of torque, it is represented at Figure 3.13, blue line represent the structural body, and red lines represent the area of propellers,

is important to mention that most of the propulsion, power module and avionics system was conducted from quadrotor prototype presented previously.

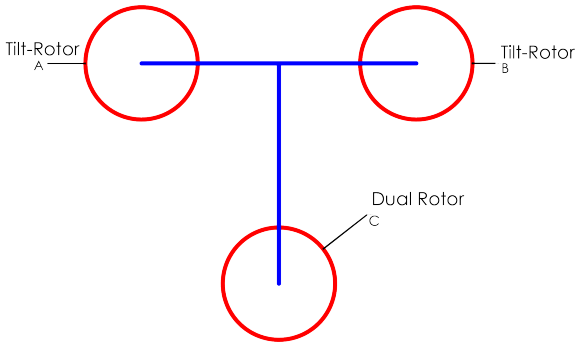


Figure 3.13: Conceptual design of Tilt-rotor configuration, A & B markers for Tilting rotors and C marker for Dual rotor placement.

The hypothesis create for this aircraft is related to u velocity, which would be controlled by tilting rotors, these mechanisms would have the capabilities to control the aircraft and have flights pitch-less.
Differential actuators are capable of rotating each rotor in a direction desired, with this dynamic, it could be performed more maneuvers and as mentioned before simplifying others, that allows stable flights with payloads that are sensitive to changes in angles.

Convertible aircraft allow the use of rotatory wings and fixed wing [25], but in this case, it is used just the principal structure, getting just rotatory wings behavior to taste their dynamics on this configuration and have characterized them for the final prototype.

3.2.2 Design Methodology

The design of this aircraft becomes simpler with the quadrotor methodology develop previously, results obtained from that design are used for that purpose, those are

propeller positioning, avionics placement, and modular components. Adaptations should be used for extra mass adhesion, due to newer actuators, and increases the rigidity of the structure for larger arms.

Using a recursive method, on this step are use prevoius data and add new parameters as placement of the components. Adaptations would not be necessary for conceptual design due to data obtained before, at Figure 3.14 it is shown the positioning of components with the adhesion of the newer actuators, those are at the center of aircraft, shaded at the diagram (D & E markers), and avionics would be shared with the previous prototype, it is just relocated at other position for convenience (C marker).

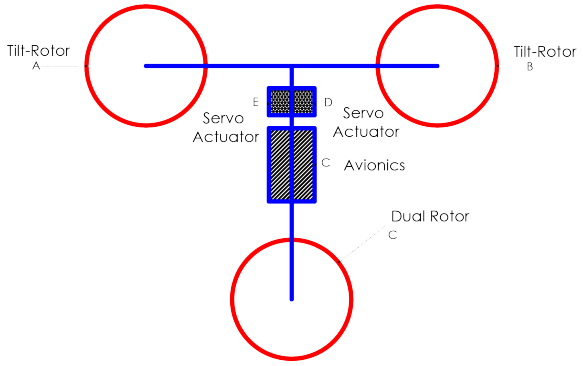


Figure 3.14: Positioning of essential components, C marker for avionics, D & E markers for servomechanism.

3.2.3 Structure

It used 3 types of structures to develop this prototype, slab based, hexagonal beam, and a combination of them, due to the complex of holding the forces that are produced for this aircraft, out of larger arms that induce a higher torque, at beam field this would induce a structure buckling, and this produces a deflection on structure, that is directly a perturbation of the whole system, due to shifting the rotors to a directions unknown.

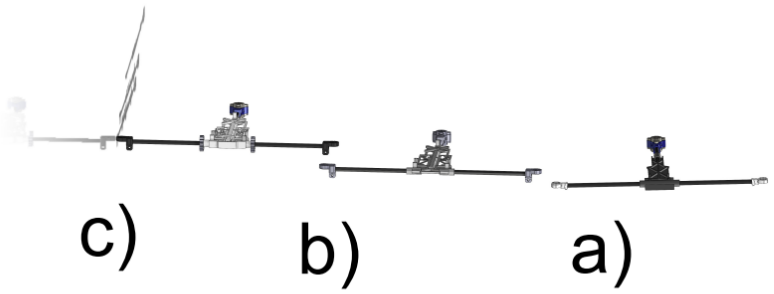


Figure 3.15: Representation of the 3 models that are selected to been use at prototype, front plane. a) model base on slap structure, b) topological optimization of the model, beam-base, c) model optimize after stress analyze.

Figure 3.16 it is shown a top representation of the 3 models that were selected for the structure prototype, a) slab based structure, which is the lightness but it has a tendency to blend, b) beam-based structure with structures for avionics installation, arm reactions at structure c) hexagonal beam based, with close loop structure, strongest but heaviest, these designs were performed with some considerations based on experience and others researches [30], [55], [62], they use similar structures as those one design at Figure 3.15, for better results it would be chosen using some parameters, especially bending parameters, that would be performed at following section of simulation. Is important to mention that structures b & c use minimal points for the placement of accessories, that to reduce mass in those designs, but in structure" a" the slab is also part of the stiffness of this part.

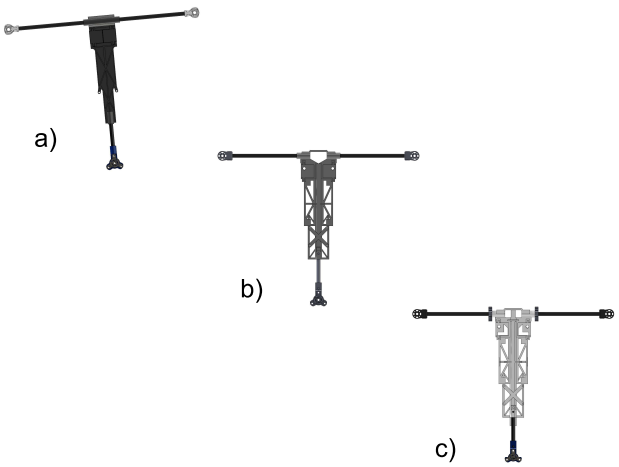


Figure 3.16: Top plane of structures intended for Tilt-rotor prototype, seeking mass reduction as well as rigidity. Time-line of optimization process a) slap base, b) optimization beam-base, c) hexagon beam FEM optimize.

3.2.3.1 Simulation

To decide which structure could accomplish the requirements of this prototype with minimal mass, it is used ANSYS Workbench simulating some forces applied to this structure and getting as results equivalent stress, deformation, and directional deformation, as parameters for this simulation were used those presented in Table 3.2, those selected from estimate thrust force produced by each rotor and selecting as material ABS, the kind of simulation selected was static structural analyze, this to test these structures at maximum thrust but avoiding some dynamics that should be less considerable than the maximum force applied to the structure.

Parameter	Value	Description
Force (individual)	3.92N	Force applied to each surface where it correspond a rotor
Fixed point	1	Support point to simulate a deformation
Rough Mesh	0.001m	Mesh in conventional areas of the structure
Fine Mesh	0.0005m	Mesh for specific areas, small parts and points of force
Assembly interface	Friction-less	Consider every assembles as rigid and unbreakable

Table 3.2: Parameters for numerical simulation, at static structural analyze.

With the parameters of table 3.2, 6 simulations were performed, creating the schematic diagram of Figure 3.17, for this case, it analyzes three of them that are those that correspond with maximum forces, and using that data it selects one of the designs, with highlight the contribution of greater rigidity and less concentration of stress.

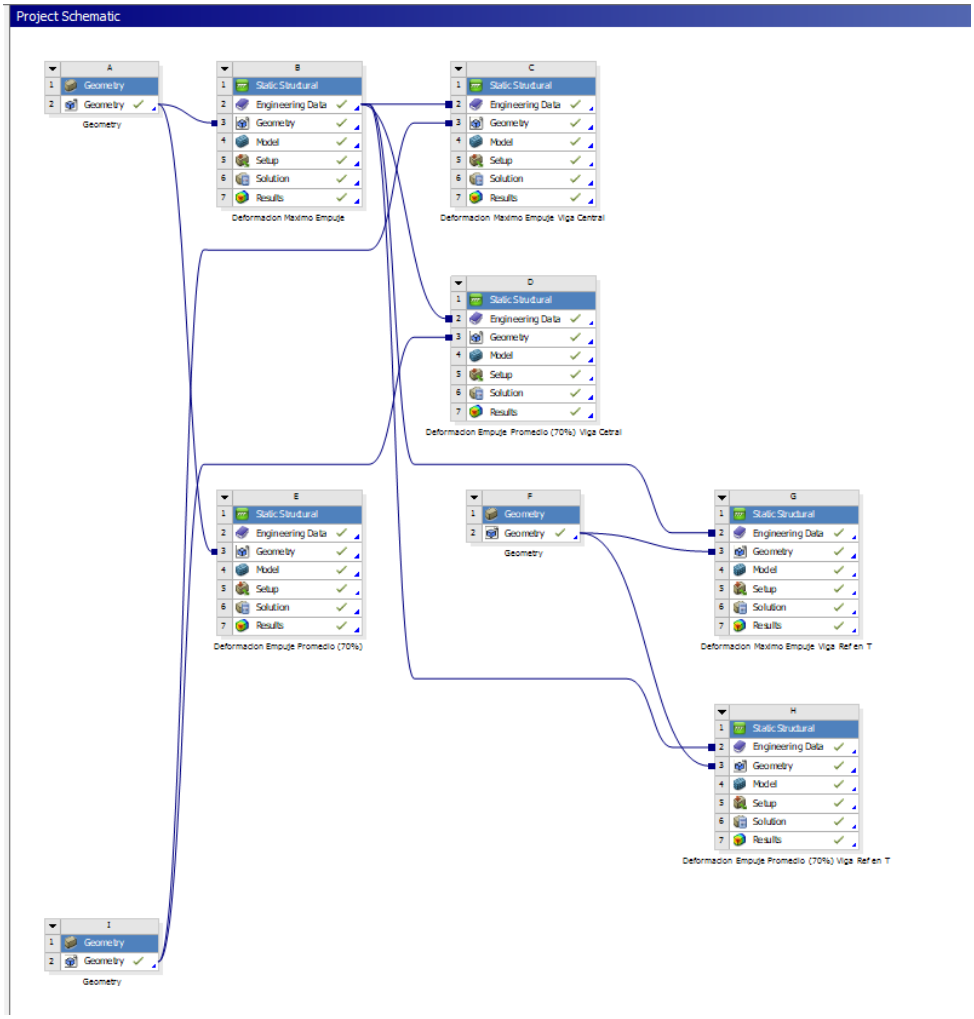


Figure 3.17: Schematic diagram of structural simulation for Tilt-rotor prototype, main body as target od analyze.

The simulation blocks of Figure 3.17 has internally a study of total deformation, directional deformation, and equivalent strain, for this case, B, C, and G block are the one used for these 3 prototypes, others are considered for cruise flight at 70% of thrust, not presented at this section due to not providing extra information for this research.

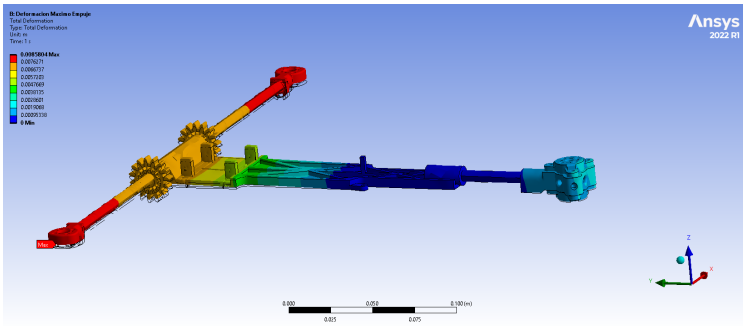


Figure 3.18: Total deformation on prototype 1, with max value of 8.5mm on X axis.

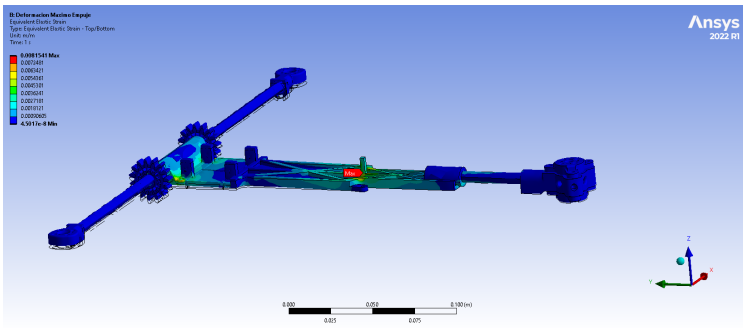


Figure 3.19: Equivalent Strain analyze on prototype 1, max point on middle slab, structural bending point estimated.

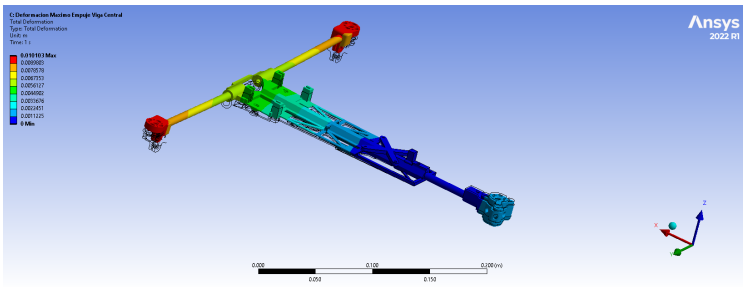


Figure 3.20: Total deformation on prototype 2, with max value of 10.1mm.

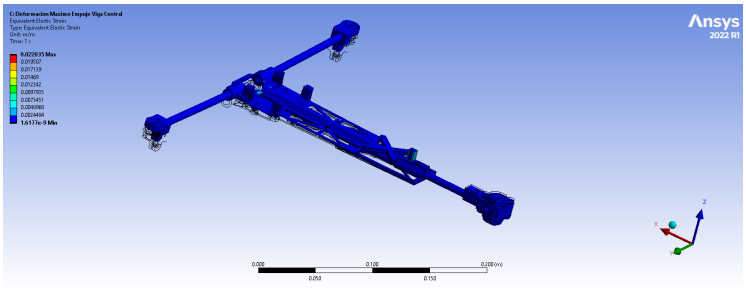


Figure 3.21: Equivalent Strain analyze on prototype 2.

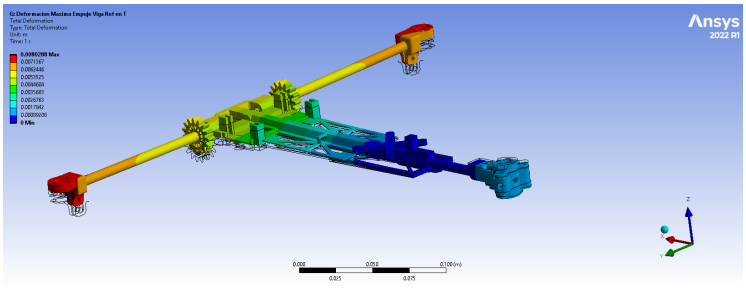


Figure 3.22: Total deformation on prototype 3, with max value of 8.02mm.

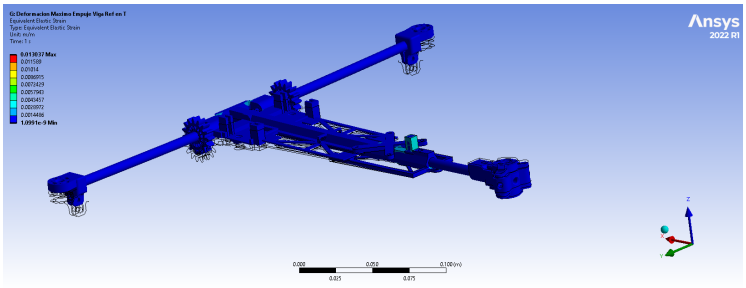


Figure 3.23: Equivalent Strain analyze on prototype 3.

From Figures 3.18 to 3.23, it is presented total deformation and equivalent strain for the 3 prototypes, where the prototype is considered as base one, used for optimization on the others, both in mass and structurally rigid, from Figure 3.18 obtained the max value of deformation that is 8.5mm concentrate on the external point of arms, behavior expected but not ideal, due to directional thrust induce by structure deformation.

Deformation behavior is considered as flutter, which is not studied in this research

just approximate a solution by structural improvement, this behavior is also similar to the beating of wings inspired on birds, not ideal for a rigid structure intended, at this case this behavior is performed by the reason of small structure for arms attachment, on the next prototype this would be re-consider using the whole wing to distribute this onto the whole internal structure.

On the other side, there is the equivalent stress which would allow us to focus the concentration points, which are those points where our part would fail and also use for the rotational axis, which in experimental parts is identified as the beating point, which in the structural field is the point to reinforce, by this reason prototype 2 and 3 are performed, absorbing that deformation with the principal hex-beam.

As the main objective, decrease or equal deformation must be accomplished and for strain, a distribution of the whole structure is mandatory. For prototype two, an open loop structure is presented, and on X axis is shown an increment in deformation, due to less area for distribution, seen in 3.20, 10.1mm of deformation on each arm but with new behavior, the whole structure bends on that axis, seen as well at Figure 3.21 where is focus the force, that in this case there are just two points, acceptable behavior for this structure.

Structure 3 is pretended as a final prototype, in that sense it should have less deformation than others as well as distributed strain, for the first parameter in Figure 3.22, is shown as a small decrease in bending (8.02 vs 8.5 mm), and well distributed, center part has less bending than prototype 2, isolating center part of those reactions, ideal for avionics systems, and strain field, it is shown a whole distribution, just a point of concentration, insignificant for this research due to concentration on an accessory point.

3.2.4 Manufacture

Like other prototypes, AM is selected for the manufacturing field, adding a multi-material approach, giving us the possibility of more freedom in force distribution,

Polylactic acid (PLA), Acrylonitrile butadiene atyrene (ABS), High impact Polystyrene (HIPS), and Polyethylene terephthalate glycol (PETG) were selected for this prototype parts, modularity and flexible assembly still on manufacture objectives, the table below it would categorize those components that are made of varied materials and a brief description.

Component	Material	Description
Motor Support	ABS (Black)	External part that is attached to vibrations of rotors.
Main Structure	PETG (White)	Principal structure of aircraft that should be resistant enough but with flex allowance to absorb high frequency and critical crashes.
Gears	HIPS (Orange, Red and Blue)	This component should be rigid and high impact resistant to gear the force of servomechanism to the main shaft of each arm.
Tail Motor support	PLA	Material rigid and dimensionally accurate to have the motor in the same position align with the principal plane to avoid induce yaw.
Tail Structure	PETG (Blue)	Part with enough rigid but resistant to impacts on collisions.
Battery Support	ABS (Grey)	Structure of the fix to attach the battery should be as light as possible, not a structural contribution.
Landing gear arms	PETG	This part elevates the aircraft to the ground at must be flexible enough to absorb impacts due to the landing an take-off process.
Shafts	Fiber Glass	Rigid shafts of low density.

Table 3.3: Components and its description of multi-material approach.

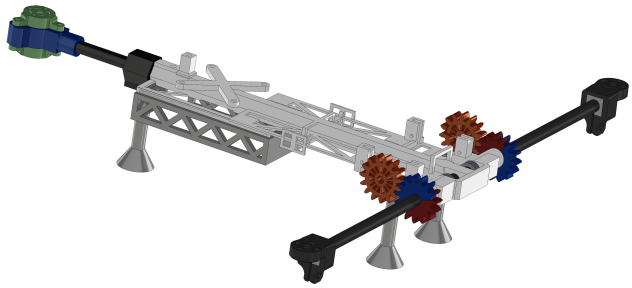


Figure 3.24: Multi-Material prototype, with different components selection for different behaviors and break-away reactions.

Table 3.3 and Figure 3.24 are shown those parts that were manufactured for this prototype, their material nature, and representation, is important to recognize its application, that aspect would be used specifically for material selection, using resistance and layer adhesion, where some parts are designed to collapse at collisions and others to be resistance enough to survive any collision where this prototype could be subject.

PETG parts mentioned in Table 3.3 are designed as structural parts that are used at critical sections, and also where is required to absorb impacts and vibrations due to propulsion or maneuvers process; another material used is HIPS, which is specially intended for support but also as gear material, due to its high impact behavior ideal for transmission of power.

Other material use, it is PLA, most common material at AM, due to its accuracy and rigidity. Especially, it is used on motor adapter and tail fix structure; As the last material use, ABS was selected, one of the most common material at the industrial field, due to its stability, thermal resistance and low density in comparison with

other polymers, nevertheless in AM this material lack in resistance due to layer adhesion which is poor if is not process at right conditions, for this application is used as lightweight material and break-away parts, expecting to collapse at collision, dissipating energy at external parts, in this case, the structures that hold de frontal motors, to not destroy the tilt mechanism.

3.2.4.1 Additive Manufacture process

Is known that additive manufacture required some consideration to produce functional parts, at this case they were processed and sliced with CURA software, and manufactured at Ender 3, Cartesian XYZ 3D printer, which allows us to use different materials without too many changes, this parts where optimize on design process giving us the flexibility of considering them solid at slicing process, at this case it where simplify, using that configuration on a slab, and for beams configurations, it is reduced with 35% and quarter cubic infill for weight reduction but maintaining enough resistance.

Was pretended to reduce the use of support for more resistance on continuous trajectories, as seen in Figure 3.25, some accessories were placed to have a more compact configuration.

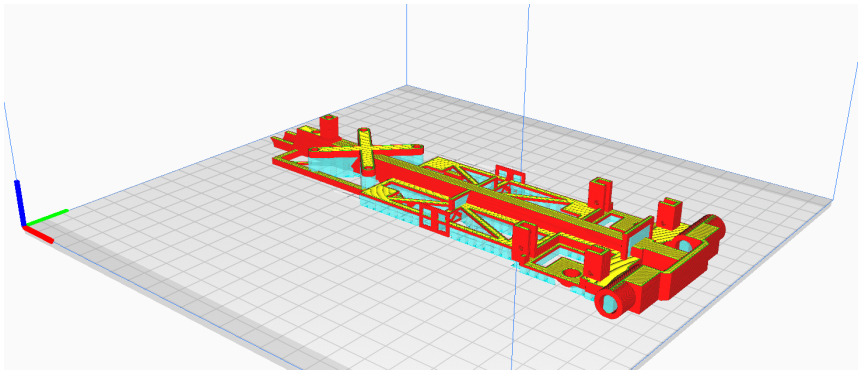


Figure 3.25: Simulation of slicing process of prototype for Tilt-rotor approach, including those supports that could be removed.

Is known that AM prototype should have modifications in a cycle of life to improve its functionality, in this case, it improves the design and tests the prototypes presented before from the left side that correspond with prototype one to the right side which is for prototype three, in Figure 3.26, which already has improvements and modifications due to the manufacturing process.

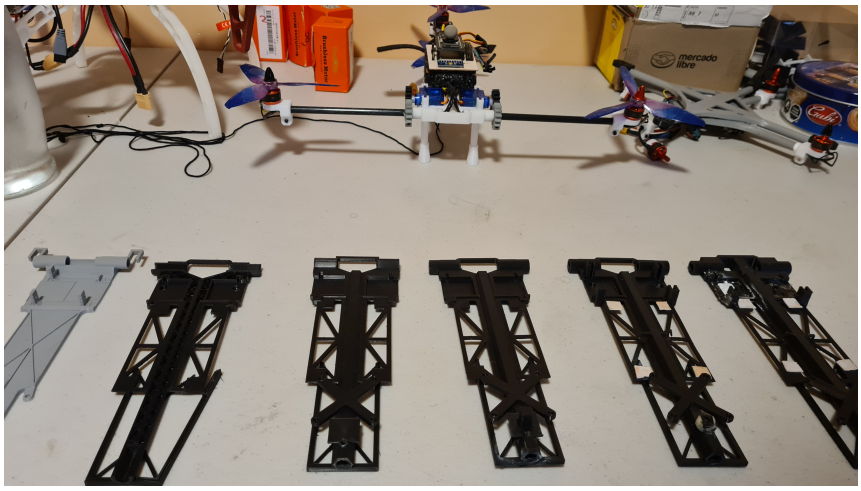


Figure 3.26: Iterations of prototype Tilt-rotor with slight changes for assembly purposes, and development form prototype 1 to 3, final result is shown at top side.

The final prototype is made on white PETG, due to better dimensional accuracy and less flexion induced by material properties, ABS prototypes were also made, Figure 3.27 illustrate that prototype, which was discarded at its assemble, due to flexion at its main hex-beam structure with hand force, which would be reflected in a problem at the time of operation, this behavior could be solved with some parameters change, but this would be reflected on more mass and for this structure is unacceptable, by this reason it was decided to change the material for one that could meet the proposed requirements.

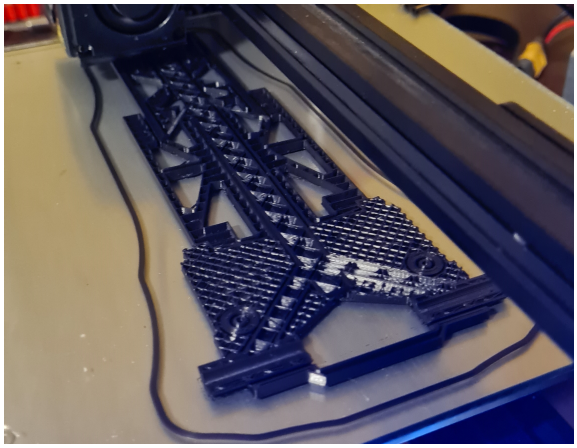


Figure 3.27: Prototype made of ABS material.

Every material has its advantage but also its challenges, for PETG based parts there is a huge consideration to meet, most of them are considered at manufacture process, as shown in Figure 3.28, some post-processing is required, as well as more demand for thermal consideration, becoming into a material that needs a similar printing temperature as ABS, as well as a closed workbench to ensure a good layer adhesion, and hard adhesion of parts with adhesives, the interface of assembly should be met by mechanical process or specialize adhesives.

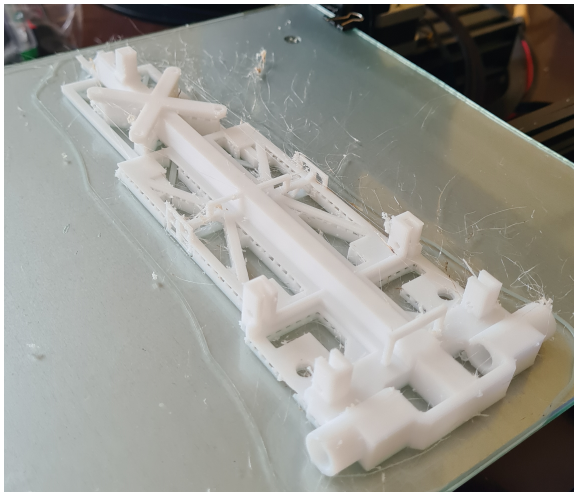


Figure 3.28: PETG base prototype for Tilt-rotor one.

The final prototype of the Tilt-Rotor project locally named "Paulie" is manufacture and assemble, with this prototype dynamics were evaluated, also avionics, rotors, and servomechanism were conducted to limits, ensuring that this configuration could be applied in the final prototype; the prototype can be observed below, in 3.29.

Figure 3.29: Tilt-rotor final prototype made of PETG with all of avionics and mechanism.

3.3 Convertible Tricopter

This prototype is named Convertible Tricopter, to describe the whole functionality of this system, a fixed wing is added to the main structure and Tricopter with 4 rotors is maintained from prototype 2, tiling-rotors are essential for this prototype, to accomplish the pitch-less function described formerly; this structure is considerably more complex than the previous in terms of the wider area of development, considering a whole structure based on an airfoil, in addition, this structure would allow to embed some components and distributed forces across the whole section, making a cleaner structure.

Is important to realize that a complete prototype should consider newer forces and behaviors, making a complex prototype design, also a rigid and reliable structure should be implemented to perform the maneuvers and transition states [60], [24]. Other elements of mechanical design would be considered on this prototype, principally center of mass, which would be an essential element to stabilize this aircraft, as well as induce angle of attack, parameters that would be mentioned below.

Differences with prototype two that become important in design are related to sizing, where the arms would be longer to fit a wing large enough to provide the necessary lift to increase the efficiency of the aircraft, as well as self-sustaining capabilities, induced by the fixed wing, or at least partially to perform cruise flight at high speeds.

3.3.1 Design objectives for wing implementation

If is use a fixed wing, it would adds capabilities, in the case of convertible aircraft it adds more states, but it becomes into a more complex system; to complete a successful prototype it is bounded to objectives for this aircraft, which are mentioned below.

- Small-size aircraft (Max 60 cm on each axis)

- Max 450g of the total mass
- Tricopter capabilities at hover mode.
- Cruise flight with a range of speed of 12-15 m/s
- Pitch-less maneuvers
- Embed avionics
- Main wing with as little obstruction as possible (<20%)
- Additive Manufacture based

For convenience, objectives were reduced, this by the reason because objectives were already accomplished by prototype two, parameters that are used for this prototype making it unnecessary to establish them again.

3.3.2 Airfoil selection

Effective airfoil design procedures require a fast and robust analysis method for on-design and off-design performance evaluation [19], recognizing the parameters that should be considered for this small fixed-wing; as mentioned on objectives 12-15 m/s are velocity target, with this initial parameter is recognize that a low Reynolds number must be used at this application, making as principal target an airfoil of high lift at low regimen.

For small UAVs some consideration should be done, endurance and low/medium velocity are variables that bonded some airfoils, making some of them unusable, by this reason search at literature for references [5] [56] [17] some that are usable for this application are ground vehicles, due to its velocity of displacement, especially F1 cars [56] that use them to keep is structure as places as possible to ground the vehicle; airfoils selected are enlisted below.

- Worthmann fx 63-137
- EPPLER 397
- SELIG S1223

This selection is inspired by cargo planes and UAVs, where a high lift and low Reynolds regimen is required, [5], the distinctive part of these profiles is the trailing edge, which in conjunction with shape creates an interaction ideal for this kind of application.

The sharp trailing edge introduces a new challenge to manufacture and safety, especially at ground maneuvers, is a delicate part, but for UAV applications and materials involved in those aircraft is not a real limitation, at least with the manufacturing process proposed.

Other parameters used in this kind of aircraft are related to an effective range of angle that is available from the wing, normally -15 to 15 degrees, but some airfoils, especially high lift ones, reduce that range, due to its lower surface, which also contributes to a differential on the pressure with a section of inverse behavior, allowing the nature of high lift but reducing others elements, as mentioned before. Another element to consider is the induced drag, a parameter that directly affects performance, being the resistance of that airfoil, considering that element as an efficient parameter and propulsion minimum force to overcome.

Using airfoil data from "airfoiltools" those three airfoils selected before are compared according to minimum energy loss criteria, using C_l and C_d as input parameters, also surface area, and wind speed. For every one of these selections, is need it the Reynolds number where this aircraft operates, using equation 3.1 is estimated as the Reynolds number for this application.

$$R_e = \frac{\rho v \ell}{\mu} \tag{3.1}$$

This design uses 12 to 15 m/s as airspeed, and also conventional states for density and ambient interaction giving the approximation of kinematic viscosity of the fluid to 70000, making a simplification of inputs need it at equation 3.1, considering as

air constant ρ and μ being a relation of viscosity, which in terms of precision is negligible for this range selection, data from tables of "airfoiltools" consider wider ranges, Reynolds numbers use for the speed range establish before, are develop below, at this case is also made another consideration where cord line is considered as aerodynamic chord line, negligible sweep angle proposed for final wing application.

$$R_e = (\upsilon)(\ell)(70000)$$
$$R_{e_{\upsilon=12}} = (12)(12.5)(70000)$$
$$R_{e_{\upsilon=12}} = 105000$$
$$R_{e_{\upsilon=15}} = (15)(12.5)(70000)$$
$$R_{e_{\upsilon=15}} = 131500$$

With those results given, data from tables of 100000 and 200000 would be used for coefficient determination.

For practical purposes, lift coefficient relations are presented in Table 3.4, and drag coefficient relations are presented in Table 3.4, giving the three airfoil characteristics, important for efficient criterion use, and the range of operation of each airfoil at 100000 Reynolds number are enlisted below.

Operational angles of attack α:

- FX 63-137: -7.75 to 18.5°
- E-397: -8.75 to 19°
- S1223: -5.5 to 11.75°

Airfoil data give operation characteristics, for lift forces there is use C_l, allowing to select of an airfoil due to operation and vertical force that would be available to carry the whole aircraft and its payload.

On Table3.4 are snap lift coefficients for -5 to 15 degrees of operation.

Angle of attack	FX 63-137	E-397	S1223
α = -5 (°)	-0.0587	-0.1481	0.0103
α = -4 (°)	0.1218	-0.0326	0.1103
α = -3 (°)	0.2789	0.0808	0.2240
α = -2 (°)	0.4484	0.1651	0.4772
α = -1 (°)	0.5397	0.2569	1.0275
α = 0 (°)	0.6672	0.3549	1.1729
α = 1 (°)	0.7798	0.4391	1.2977
α = 2 (°)	0.9291	0.5246	1.4219
α = 3 (°)	1.0594	0.6166	1.5223
α = 4 (°)	1.1373	0.7447	1.6248
α = 5 (°)	1.2948	0.8406	1.7335
α = 10 (°)	1.6858	1.4699	1.9821
α = 15 (°)	1.7531	1.4416	NaN

Table 3.4: Angle of attack relation with lift coefficient.

On the other hand, there is drag force which is related to that force that opposes aircraft movement at the "x" axis; this coefficient is also affected by the angle of attack, by that reason is presented in Table 3.5 operational coefficients to be able to select the ideal airfoil for our application.

Angle of attack	FX 63-137	E-397	S1223
α = -5 (°)	0.04293	0.03191	0.10225
α = -4 (°)	0.03356	0.03096	0.08464
α = -3 (°)	0.02951	0.03122	0.06862
α = -2 (°)	0.02763	0.03251	0.04983
α = -1 (°)	0.02932	0.03397	0.02169
α = 0 (°)	0.02874	0.03544	0.02337
α = 1 (°)	0.02906	0.03681	0.02476
α = 2 (°)	0.02730	0.03912	0.02644
α = 3 (°)	0.02706	0.04235	0.02811
α = 4 (°)	0.02597	0.04370	0.03079
α = 5 (°)	0.02485	0.04586	0.03427
α = 10 (°)	0.03307	0.02921	0.06371
α = 15 (°)	0.08093	0.08165	NaN

Table 3.5: Angle of attack relation with lift coefficient.

Using data from Table 3.4 and Table 3.5, it is select an operation angle of 4° where 3 airfoils have enough C_l and acceptable C_D, as well as a range of operation that allows us to have freedom of maneuvers, for safety reasons, due to our objective of limited pitch angle, just having this range for inducing wind and other atmospheric conditions, also giving an equal angular displacement to both sides.
Considering aspects mentioned in previous sections, airfoil selection becomes a comparative of efficiency, range of operation, and maximum C_l, due to volume limitations. Using graphical comparative becomes a more dynamic selection, at Figure 3.30 is shown the comparative of C_l and $AoA[\alpha]$ on each airfoil, and C_D vs $AoA[\alpha]$ in Figure 3.31 both with a dashed line, which is the angle of incidence selected, using that consideration, it is shown a graphical comparative of those properties of the airfoil.

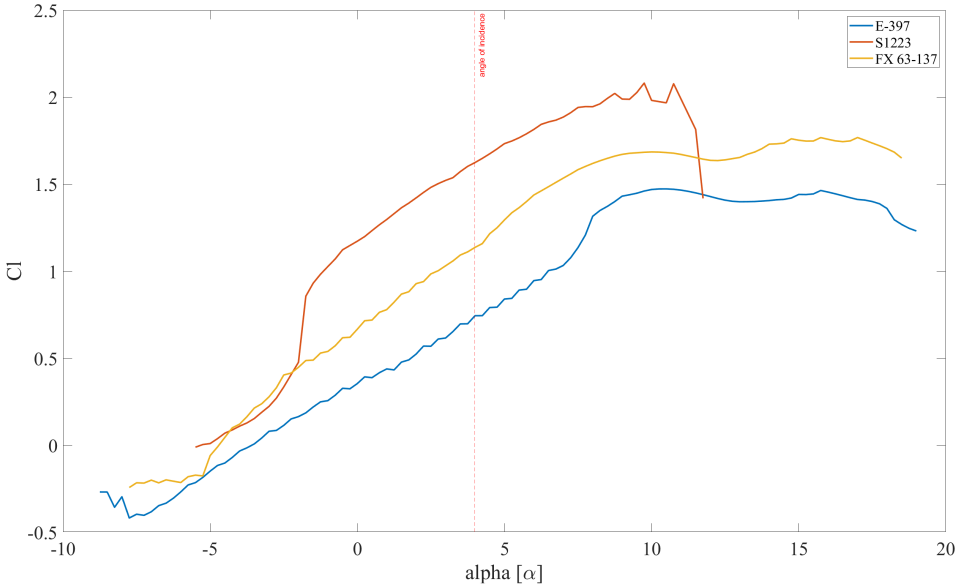


Figure 3.30: Comparative of airfoils, Cl parameter.

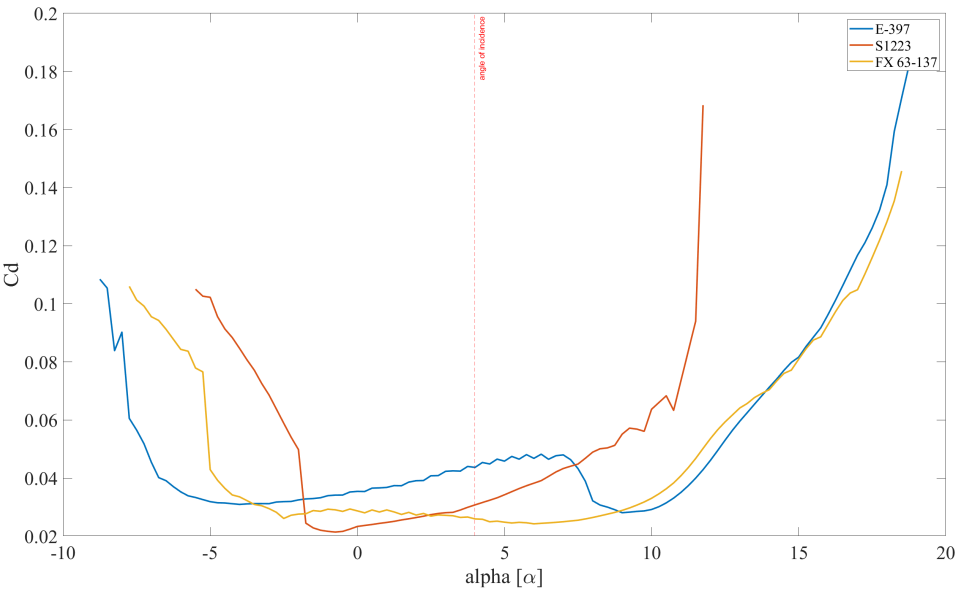


Figure 3.31: Comparative of airfoils, Cd parameter.

With those results there are make considerations; from lift coefficient [Figure 3.30], a pseudo linear behavior is expected, especially at this small size aircraft, for

that reason, the S1223 airfoil decreased influence on the final prototype, especially for its catastrophic behavior at -5 to -2 and from 10 to 12, where its change is unusable for this application, in that sense E-397 and FX 63-137, show similar behaviors, with a better performance from FX 63-137, it shown more C_l than its rival, another consideration is boundary conditions, where both airfoils shown acceptable result from -5 to 15 °; On the other hand, the C_d coefficient is important for propulsion purposes, and also for efficiency, where a good selection of airfoils should consider drag forces to be able to perform maneuvers and have enough power to them; in this case, at Figure 3.31 31 is shown those coefficients FX 63-137 and S1223 are those that have less impact and also a wider zone of linear behavior, FX 63-137 shown a more effective area and less impact on the system on the whole boundary selected for this prototype.

For this prototype, Wortmann FX 63-137 airfoil is selected due to its relation to low Reynolds numbers regimen, high lift, and its effective angle, are important for maneuvers and stability, especially stall, and lifting at high speeds, that reduction on lift coefficient affect directly on aircraft parameters to consider, and also induce angle of attack by wing position is important to realize it, that initial angle would reduce the effective area of change at angle field but would allow to have more lift coefficient at cruise flight, is important also to consider the slope of C_l and $C_d$both parameters that change with Angle of Attack (AoA), for this prototype is expected to not have AoA change, just the one induce by structure alignment, by this reason is select and initial angle and it would consider that for lift force, this aspect contributes to this airfoil, due to its stability and linear behavior on effective range use of C_l vs α and C_d vs α, limited to small changes on this angle, lest to maintain the pitch-less requirement for this convertible UAV.

Is important to mention that this airfoil is also used on other ground applications, especially at F1 races [56], performing tasks of heavy-duty endurance, complex forces concentration, and dirt airflow allowance, giving excellent results, there is just one consideration, it is fragile on its trailing edge, due to its shape [5].

3.3.2.1 Forces develop by airfoil

For this airfoil selected, there are forces developed at running conditions, those that we would use are the lift and drag forces. For lift force, it is used equation 3.2, and for drag force, it is use equation 3.3; for this case is ignored to induce drag due to other vortex interactions such as rotors, which would be examined in future works.

$$L = \frac{C_l \rho v^2 A}{2} \tag{3.2}$$

$$D = \frac{C_d \rho v^2 A}{2} \tag{3.3}$$

This work is only analyzed the cruise flight state, and it is simplified, not considering aspects as external reactions, it only develops the ideal forces. For lift force, C_l localizes from Table 3.4, and uses local data:

Parameter	Development	Result
Lift (L)	$L = \frac{(1.1373)(1.13)(12)^2(0.075)}{2}$	6.93N
Drag (D)	$D = \frac{(0.02597)(1.13)(12)^2(0.075)}{2}$	0.1585N

Table 3.6: Lift and Drag numerically development.

Is important to clarify that those values on table 3.6 are ideal, with optimal distribution and non turbulent flow; is known that low Reynolds numbers would develop inconsistent flow adherence, and for that reason is expected a 70% of that values, as well as other elements to consider, in future works could be implemented lifting line theory to correct that values, but for this case would be considered ideal to develop and validate this prototype with physical test.

3.3.3 Manufacture

The main philosophy of this prototype is to consider the whole system as a unique part, with the internal structure for components attachment and adhesion of external parts for accessories, propulsion, and components needing to be accessible by the user, by this reason the main structure is the fixed-wing, for vortex and mass reduction is proposed a swept wing, with a center cord 2 times bigger than external ones, max dimension was established by the max diagonal of the workbench, making a relationship be- tween design and manufacture.

At conventional wing manufacture, there are use skin, ribs stringers, and spars, manufacture, and materials implemented allow uses without compromising the aerodynamics, always keeping in mind that the wing contour within the chord-wise direction must be guaranteed [17]; at small aircraft is harder to use that kind of manufacture due to miniaturization of parts and materials properties, where one of the most important values at this topic is mass, it could not accomplish the structural demands with conventional materials, by this reason are applied other manufacture techniques, increasing properties with geometrical arrays and multi-material approaches, for this prototype AM is proposed, to implement that techniques.

3.3.3.1 Additive Manufacture adaptation

Additive Manufacture (AM) is a technique based on planar slides, where each part is segmented into small slides that are joined together with 3-axis mechanics, allowing the development of non-conventional parts, there is a different kind of AM processes, but those are already mentioned before, as well as material selections, at this section is focused on wing manufacture.

UAVs based on AM are complex designs due to the anisotropic behavior of this technique, where is important to select planes order, orientation, and flex module, on wing-based parts it is a complicated task due to mixed forces, for this devel-

opment is selected as the preferred parameter the geometrical accuracy, giving an orientation equidistant to the cord line, as shown in Figure 3.32, where this face of the airfoil must be placed at the workbench, and creating a fragile plane on ”y” plane, becoming into the failure plane, for that reason it is selected a multi-material implementation, where it would be used a compound material rod, which absorbs that force distribution as well as been an effective axis for tilting rotors actuators.

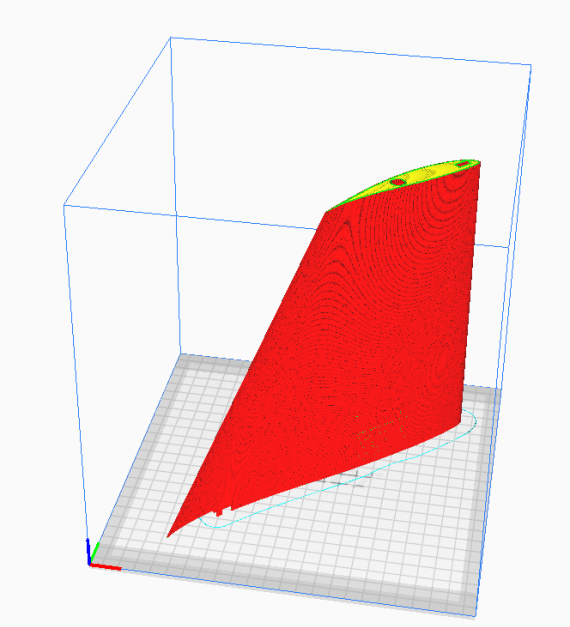


Figure 3.32: Orientation of Semi-wing at workbench.

This prototype must accomplish a mass optimization to be able of its missions accomplish, for that reason it is designed with a minimal material infill, using surface approaches and minimum connection lines for geometrical accuracy without deformation on post-processing and operation, by this reason, it is select the main construction material, which is ABS, due to its low density in comparison with other AM materials, this material allows a minimum length of 16mm [27], [22], that on the linear case, but for this design it is presented an airfoil based on splines, with give us a complex line that is shorted but in this sense, it is a maximum value for trajectory, not axis measurement; using that considerations it is designed the internal structure of the wing, shown in Figure 3.33, which has 14.6mm of space between

lines, is identical just trim by the external airfoil boundary.

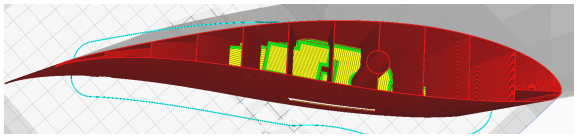


Figure 3.33: Internal material distribution for semi-wing.

Other parts of this prototype were designed with conventional methodology, that reason it would not be mentioned in the drawing process, as well as been repetitive with the other two prototypes.

3.3.3.2 Multi-material

A small prototype is a huge development process, due to the miniaturization of components and materials selections, at aerial vehicles is mandatory to have as less material as possible to perform an efficient flight, or in some cases just to be able to take off; an interrelation between power module, propulsion and total mass of the aircraft must be considered, due to limitation on max thrust perform by propulsion units as well as power module (especially battery) that are limited by electrical characteristics. Considering those parameters mentioned before, it is proposed a multi-material application, where are use lightweight materials at points that are compatible with their physical properties, and at other points use external materials of AM reinforce or absorb forces and distributed on the whole structure. Is important to mention that is only considered as materials that are part of the structure, sensors, actuators, and propellers power units are not considered as part of this section, due to their non-interchangeability or optimization, they are mandatory to be used as designed by their manufacturer. To visualize that multi-material approach, Figure 3.34 is presented.

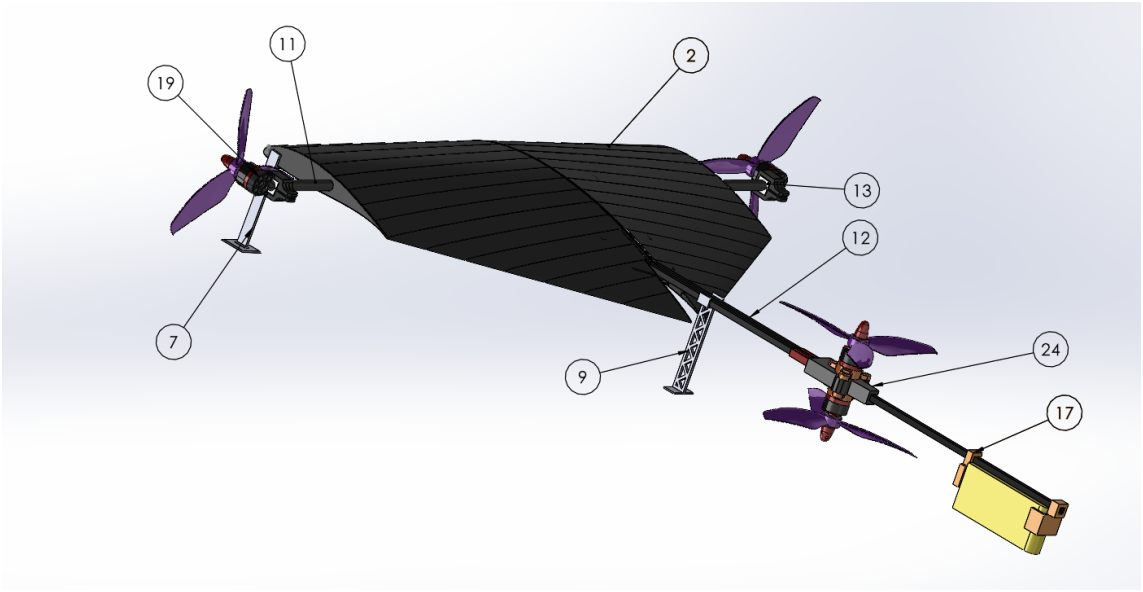


Figure 3.34: Multi-Material visualization of Dorito prototype.

The representation shown in Figure 3.34 is part of the whole prototype design, for that reason indicators are not consequent, those represent a specific part of the whole prototype, being unique.

The material used are ABS, PETG, PLA, acrylic resin, carbon fiber, and glass fiber, each of them has different physical properties, and different methods for processing, for small parts and noncritical ones it uses acrylic resin, that came from SLA printing, that on 7 and 9 components, those one represent pads that rise the model as well as working as the undercarriage, becoming into replaceable components, by that reason it is used as less as possible material on them; other material use is ABS, this one has advantage on lightweight and thermal resistance, use at whole wing, represented by number 2, this is also flexible, important at this point for collisions but not ideal at dynamics, getting aero-elasticity, by that reason, it is used a reinforced material, for this case glass fiber tube, expected at 11 part, which is also a rod for actuator angular movement is transferred to rotors, the main mechanism for tilting rotors. Other reinforcement materials are the squared carbon fiber tubes, which are structural parts for tail rotors, in this case, they are joined with each semi-wing, getting as possibility its separation. 13 and 17 components are made of PLA to

have perfect accuracy, been fixture parts, use for localization and assembly by that reason that requirement, and as last material, it is PETG used at those parts that are in contact with heavy-duty components, as well as thermal behaviors, those are 24 and 19, both of them are in contact with rotors, parts that produce the main forces, irradiates heat, and produce vibration, a reason to consider a material that allows flexibility, use for high-frequency vibrations dissipation.

3.3.4 Convertible Tricopter phases

For convertible aircraft, there are operation phases, defined as a set of states of actuators, structures, and surfaces that are delimited to a type of operation, for UAVs, there are use hover (slow speed movements) [12] and cruise flight (high speed) [52], those are particular kind of flight for multi-rotors and fixed-wing aircraft respectively, for convertible aircraft both of them perform and by that reason are consider as phases.

On tilt-rotor aircraft those phases mentioned before, are represented by the angle boundary on the rotor angular direction, hover is limited to small changes across 0 angle, and for cruise flight at the 90s [30], is important to mention that those changes are established by aircraft,s designer which estimates which ones are useful for that aircraft.

Our prototype it is proposing two phases, same as mentioned before, hover condition, as shown in Figure 3.36,, is important to mention that is considered a continuous system, for that reason those states are only demonstrative, in real operation, it would have a nondelimited movement, the operator could send a full tilting trigger signal and it would change between states actively it is necessary or if the control re-queried that.

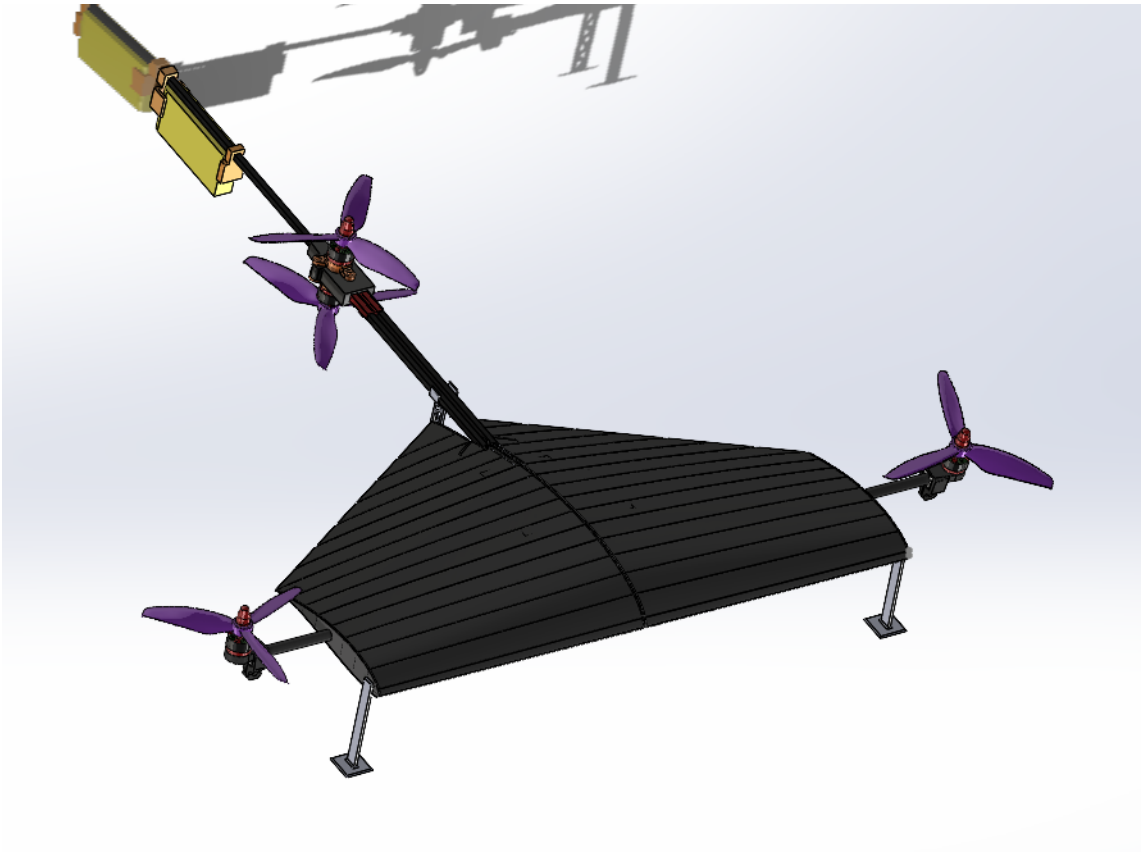


Figure 3.35: Tilting rotors hover phases for Dorito´s prototype.

This prototype is based on differential tilting movement, for that reason it could be used as offset as well as output signals, having wider states capabilities, as well as fine control correction due to its multiple actuators, which allow the modified system behavior according to phases or to mixing algorithm implemented.

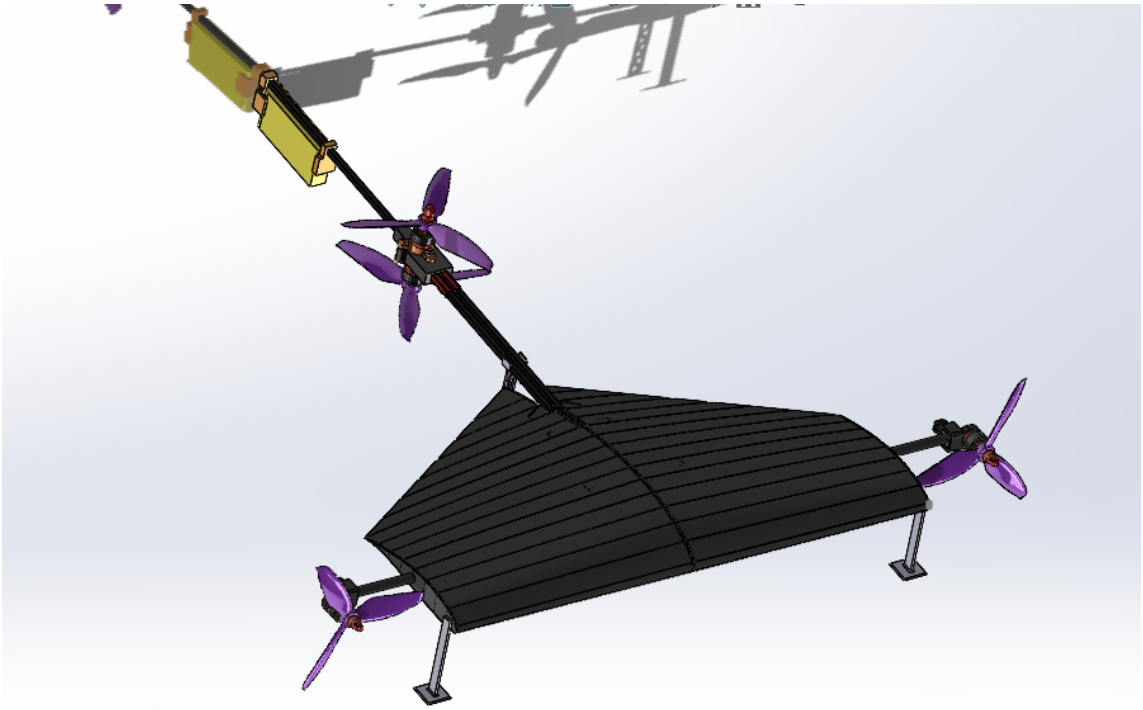


Figure 3.36: Tilting rotors cruise flight phases for Dorito´s prototype.

As a methodological result, this aircraft is designed with hybrid capabilities in mind, by that reason are selected variations, phases, and components distributions, becoming a prototype that allows us to use actual paradigms as well as other proposed, principal benefits of this convertible aircraft, belongs to its equilibrium of forces that could be also detached to produce others behaviors that are not part of multi-rotor o fixed-wing based aircraft. As the final manufacture prototype, it is developing the aircraft into a real prototype as seen in Figure 3.37.

Figure 3.37: Prototype "Dorito" final manufacture.

Chapter 4

Equations of Motion

An important topic to study is related to systems dynamics behaviors, where it described how a system works and has been part of the modeling field at control scope; equations of motion govern those behaviors, with limitations, those are effective as the description of dynamics included at them.

It is possible to describe multiple systems with the same equations, but it would lack on some points, at this field a specific equation for each system would perform better, for that reason is paid special attention on this point, performing a different design for each aircraft presented at this work, some relations between them are also defined at this section; as the equation of motion are use Newton-Euler approach to define dynamics, physical inputs, internal behaviors, degrees of freedom, and other points to propose a model for each aircraft.

As the main description for each system, it is use reference frames definition, Newton-Euler formulation, orientation, and position dynamics model establish becoming into the description of each aircraft configuration presented and its behaviors.

4.1 Reference Frames

This section is related to establishing conventions for frames, which allow us to have movement conventions, in that sense it would be possible to determine aircraft states and use them for guidance and navigation systems, in other words, it is the coordination between relative frames and absolute ones, for that reason is defined axis system at Euclidean space below:

- fixed frame establishes at the ground, used for reference at translation movements, as well as for references at orientation angles. It is represented as: $I_n = \begin{bmatrix} x_{I_n} & y_{I_n} & z_{I_n} \end{bmatrix}$
- Body frame: a frame defined at the center of mass of each aircraft to define those movements relative to them, is also important as a measurement reference for the inertial frame at orientation and those physical effects that are affected by environmental conditions. This frame is represented as: $B_n = \begin{bmatrix} x_{B_n} & y_{B_n} & z_{B_n} \end{bmatrix}$
- Aerodynamic frame: interaction of forces frame for the wind to aircraft relation, the surrounding wind is dependent on the relative direction to aircraft, in that sense is necessary a definition of a frame that allows us to characterize that reference for a correct force and aerodynamic momentum. It is established as:
  $W_n = \begin{bmatrix} x_{w_n} & y_{w_n} & z_{w_n} \end{bmatrix}$

Reference frames are represented in Figure 4.2, using North-East-Down (NED) convention (figure 4.1),), to stand out, those three reference frames belong to a special Euclidean group SE(3), due to that condition rotation with the orthogonal matrix are allow. Is also important to mention that in this case three different prototypes are studied, for practical representation, all of them are represented with the same principle, becoming a repetitive topic and a definition for each aircraft, for that

reason it is use same references.

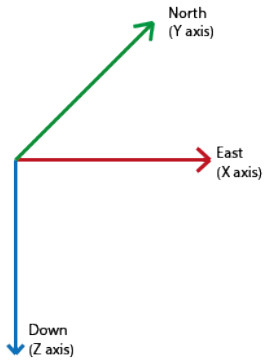


Figure 4.1: North-East-Down (NED) convention.

For symmetrical structures, there is no problem with wind frame placement (quadrotor structure), but for those other based on tricopter structure, is important to place them according to aerodynamics effects, there is no math difference but at reference scope, it becomes complex to mix them with those scopes.

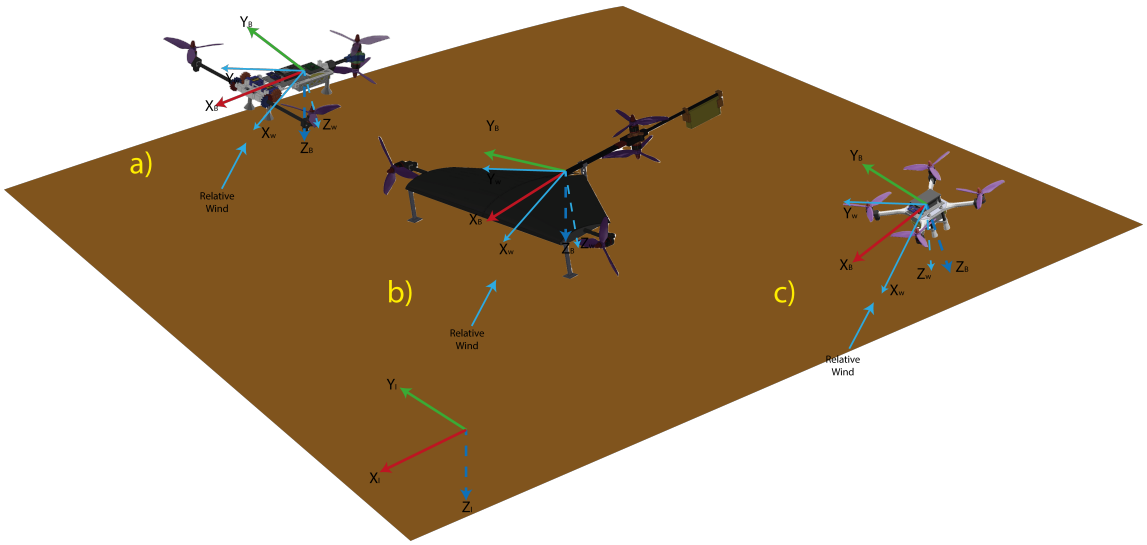


Figure 4.2: References Frames for all of prototypes, a) Tilting rotor prototype, b) Tilt-rotor with fixed wing, c) Multi-rotor.

Figure 4.2 are shown the reference frames for each aircraft, it is important to see the relation between them, they have selected at same references to standardize these frames in this work. It uses green as the "y" axis, red for the "x" axis, and blue for the "z" axis, at the body and inertial frames, which are separate enough to allow that convention, but in wind frame, it uses light blue to represent all those axes with its respective notation, and wind relative direction. With those different frames establish, it is possible to produce some interactions between them, most of them are related to angle interactions, where a difference between a direction in one frame to another would be represented as those angles of divergence, for aircraft stuff some of them are important, for orientation, there are Euler angles, aerodynamics ones are also included, those angles are enlisted below. For aircraft orientation, there are defined Euler angles:

- ϕ: angle defined between y_B axis and a resultant plane from x_I and y_I
- θ: angle defined between x_B axis and a resultant plane from x_I and y_I
- ψ: resultant angle from a perpendicular plane of x_n and y_n cut by x_B and x_I axes.

Those definitions allow us to orientate our aircraft in a delimited space, allowing stabilization of them.
On the other hand, there are the angles previously mentioned that are related to aerodynamic effects, are:

- α (angle of attack): angular relation between x_B axes and x_W and y_W plane.
- β (drift angle): projected angle from x_B and x_W and y_W plane related with original x_B axis.

With previous definitions, it is possible to define equations of motion of these prototypes, in this case, they would have a relationship, just adding terms that are

presented by each configuration paradigm, but also allow us to place each aircraft at a defined space for orientation and navigation purposes, just its added tilting frame to define the actuators for equations of motions, but as been a non-general frame it is speared at section below, which is only applicable for tilting rotor systems.

4.1.1 Tilting-rotor frame

For the tilting-rotor system of these aircraft configurations, it is possible to establish a tilting frame, where all the tilting rotors are presented, in this case, frontal rotors are those.

This frame is defined as a rotating frame, about y_R, defined with x_{R_1}, z_{R_1}, and x_{R_2}, z_{R_2} with tilting angles as δ_{R_1} and δ_{R_2}, as seen in figure 4.3 upwards position is 0° while forwards is -90° according to NED and right-hand rule.

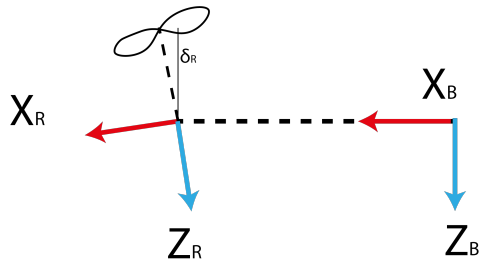


Figure 4.3: References frame for angular tilting rotation.

4.2 Multirotor scope

The first prototype analysis is defined as a quadrotor system, that to accomplish the requirements of prototype one, as well as to use it for comparative purposes. A quadcopter with an "X" configuration is selected, and symmetrical distribution is also selected, that to have a center of mass located at the center of the whole structure, that for" x" and "y" planes, for "z" based ones, would be located as near

as possible to the propulsion length, that to have rotational axes allied to them a reduce control forces.

4.2.1 Newton-Euler representation

For equations of motion, definitions are necessary a formulation that allows us to describe the degrees of freedom (DoF) that govern this aircraft, for that objective, it is selected the Newton-Euler formulation, which allows a relation between DoF and translations.

In simplified form, it uses the second law of Newton, which establishes that the time rate of change of the momentum of a body is equal in both magnitude and direction to the force imposed on it, which allows us to define it as:

$$m\dot{V} = F_I \tag{4.1}$$

where m represents body mass, $\dot{V}$ is the relative acceleration vector to the inertial frame, and F is the force vector that represents the entire system interaction, in simplified form, a better representation of the forces at the aircraft field is separated into frame-based forces as the following equation:

$$m\dot{V} = RF_B + F_I \tag{4.2}$$

In another field there is the orientation of aircraft, which could be represented by the generated moment due to forces presented, relative to the body frame it is represented as:

$$J\dot{\Omega} = -\Omega \times J\Omega + \tau_a \tag{4.3}$$

where $J \in \mathbb{R}^{\Vdash}$ describes the inertial moment matrix, for angular velocity it is represented as $\Omega = \begin{bmatrix} p & q & r \end{bmatrix}^T$, and for the torque τ_a which represents torques generate by aircraft forces.

4.2.2 Attitude Dynamics

General orientation at aircraft is required a punctual definition, where a general representation was presented in equation 4.3, specific parameters such as inertial matrix and torques generate a vector, and are required to include quadrotor behaviors into a vector that allow us to absorb the whole extra dynamics, as gyroscopic effects due to rotors, aerodynamic effects, and others. The main general dynamic of the aircraft is presented below.

$$\dot{R} = R\hat{\Omega} \tag{4.4}$$

$$J\dot{\Omega} = -\Omega \times J\Omega + \tau_a + D_\eta \tag{4.5}$$

At equations 4.4 and 4.5, internal terms should be expanded, those are present below to clarify the aircraft parameters integration.

For angular velocity it is use $\hat{\Omega}$, this is an anti-symmetric matrix, representing the angular velocity of pqr at the body frame, represent below:

$$\hat{\Omega} = \begin{pmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{pmatrix} \tag{4.6}$$

At the torque field it is represented by τ_a, which is defined at the center of gravity, which corresponds to the body frame, with the four forces of rotors it is possible to represent the vector as below:

$$\tau_a = \begin{pmatrix} \tau_\phi \\ \tau_\theta \\ \tau_\psi \end{pmatrix} = \begin{pmatrix} d[(f_1 + f_3) - (f_4 + f_2)] \\ d[(f_3 + f_2) - (f_1 + f_4)] \\ Q_1 + Q_2 - Q_3 - Q_4 \end{pmatrix} \tag{4.7}$$

where d represents distance aligned with aircraft axes from the center of gravity, f represents forces from each rotor, and the moment of reaction from rotor blades due to drag, that at Q, it is expanded at equation 4.8

$$Q_k = \rho_a A_{a_k} \omega_k^2 r_k^3 c_{Q_k} \tag{4.8}$$

using k as rotor identification, as shown at figure 4.4, C_{Q_k} as a momentum coefficient dependent of geometrical and aerodynamics characteristics, ρ_a a well-known parameter, air density, other parameter is ω_k which is angular velocity y as final on, it is r_k semi-wingspan of the propeller.

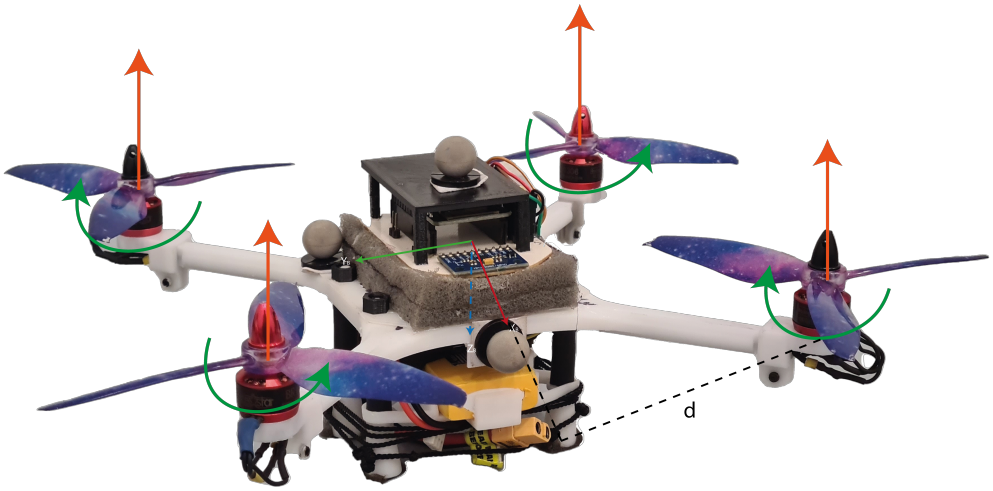


Figure 4.4: Quadrotor Forces and rotors directions.

For gyroscope and aerodynamics effects it is used D_η, defined as below:

$$D_\eta = \begin{pmatrix} d_{\eta 1} \\ d_{\eta 2} \\ d_{\eta 3} \end{pmatrix} = d_{\eta gyro} + d_{\eta aero} \tag{4.9}$$

Gyroscopic momentum effects are expanded as equation 4.11, where that summary allows us to integrate those rotors effects, important for stabilization purposes.

$$d_{\eta gyro} = \sum_{k=1}^{4} (-1)^{k+1} I_{r_k} [\Omega \times e_3 \omega_k] \tag{4.10}$$

Also, aerodynamic forces are involved, in this case at $d_{\eta aero}$, where there are included forces and aerodynamic effects due to the interaction between the aircraft body and

free stream, defined as:

$$d_{\eta aero} = \begin{pmatrix} \mathcal{L}_n \\ \mathcal{M}_n \\ \mathcal{N}_n \end{pmatrix} \tag{4.11}$$

Those moments of inertia are related to the body frame, where $\mathcal{L}_n$, $\mathcal{M}_n$, and $\mathcal{N}_n$ are x_B, y_B and z_B respectably, that for rotatory blade systems [23].

4.2.3 Translation Dynamics

Positioning dynamics are the result of angular motion characterization, with it is possible to orientate forces and linear actuation of an aircraft; it is possible to define forces at different frames to analyze the entire system and be able to control them, by that reason it is necessary to expand those terms mentioned before at equation 4.1, giving:

$$F_I = mge_3 + D_\xi \tag{4.12}$$

where D_ξ include the whole external forces interactions, as mentioned in the previous section; in the same way is necessary to define body forces, in this case, are attached to the aircraft allowing us to summarize them as the vector of the equation 4.13 for forces, as well with that consideration it is possible to say that thrust vector is defined as equation 4.14.

$$F_B = (f_1 + f_2 + f_3 + f_4)e_3 \tag{4.13}$$

$$T_T = \begin{pmatrix} 0 \\ 0 \\ \sum_{k=1}^{4} f_k \end{pmatrix} \tag{4.14}$$

Been establish those forces vectors is possible to say that position dynamics are defined as:

$$\dot{\xi} = V \tag{4.15}$$

$$m\dot{V} = R(-T_T) + mge_3 \tag{4.16}$$

where ξ represents position relative coordinates to an inertial fixed frame, been its derivatives V for linear velocity, D_ξ aerodynamics forces, and $\eta = \begin{pmatrix} \phi & \theta & \psi \end{pmatrix}^T \in \mathbb{R}^{\not\vdash}$ describing aircraft's angles of rotation. With an orthogonal rotational matrix is possible to expand equations of motion to a parameterized system defined by Euler angles, developing these equations, force, kinematics, and moments respectively.

$$\begin{aligned} \dot{v}_x &= -\tfrac{f_T}{m}\left(\sin\psi\sin\phi + \cos\psi\sin\theta\cos\phi\right) \\ \dot{v}_y &= -\tfrac{f_T}{m}\left(\sin\psi\sin\theta\cos\phi - \cos\psi\sin\phi\right) \\ \dot{v}_z &= -\tfrac{f_T}{m}\left(\cos\theta\cos\phi\right) + g \end{aligned} \tag{4.17}$$

$$\begin{aligned} \dot{\phi} &= p + q\sin(\phi)\tan(\theta) + r\cos(\phi)\tan(\theta) \\ \dot{\theta} &= q\cos(\phi) - r\sin(\phi) \\ \dot{\psi} &= q\sec(\theta)\sin(\phi) + r\sec(\theta)\cos(\phi) \end{aligned} \tag{4.18}$$

$$\begin{aligned} \dot{p} &= \left(\tfrac{J_{yy}-J_{zz}}{J_{xx}}\right)qr + \left(\tfrac{1}{J_{xx}}\right)\tau_\phi \\ \dot{q} &= \left(\tfrac{J_{zz}-J_{xx}}{J_{yy}}\right)pr + \left(\tfrac{1}{J_{yy}}\right)\tau_\theta \\ \dot{r} &= \left(\tfrac{J_{xx}-J_{yy}}{J_{zz}}\right)pq + \left(\tfrac{1}{J_{zz}}\right)\tau_\psi \end{aligned} \tag{4.19}$$

With those, it would be possible to design guidance and navigation control algorithms at incoming sections.

4.3 Tilt-rotor scope

UAVs based on Tricopter configuration use four rotor configurations, which allows us to have a balanced system, which would be represented below; it is important to mention that these systems are related, so cross-references are used to avoid rewriting functions, just matrix and vectors that introduce those dynamics of tilting-rotors would be thoroughly examined.

For this case, there are no added forces, just direction change of those already present, as well as their configuration distribution, by that reason matrix and vectors would be rewritten, but equations 4.1, 4.2 and 4.3 are interpretations of Newton-Euler systems.

4.3.1 Attitude Dynamics

The general dynamic of the aircraft is described in equations 4.4, 4.5, which are considered a generic form of a relation between the body frame and Euler angles at the inertial frame, which in that sense are shared at all of these prototypes, as well as angular velocity equation (4.6), which is characteristic of rigid bodies to its center of mass.

For orientation purposes, is important to define the location of the forces, which in this case is developed in Figure 4.5:

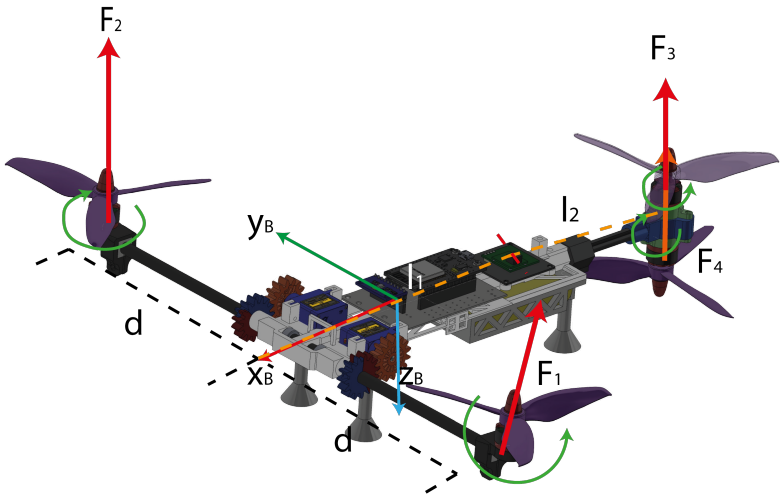


Figure 4.5: Tilting-rotor prototype Forces directions.

Where d stands for arm length, l_1 and l_2 for distances to the center of mass, and F_n for each rotor forces produce.

The first consideration of this system is related to the torque matrix, which includes

locations of rotors and interactions with the center of gravity, making dependence on directions, which in this case is important due to tilting behavior.

$$\tau_a = \begin{pmatrix} \tau_\phi \\ \tau_\theta \\ \tau_\psi \end{pmatrix} = \begin{pmatrix} d(f_1 - f_2) \\ l_2(f_3 + f_4) - l_1(f_1 + f_2) \\ Q_1 + Q_3 - Q_2 - Q_4 + f_1 \sin(\delta_{R_1}) - f_2 \sin(\delta_{R_2}) \end{pmatrix} \tag{4.20}$$

Is also applicable to this system, especially if we consider that angle of attack would change with tilting movement, other elements are those presented in equations 4.9, 4.10, and 4.11, which are related to gyro and aerodynamic effects, those are generic terms, giving the possibilities of using them, for gyro considerations it has the same number of rotors which induce same behavior, just change inertial matrix, which is characteristic of every system; for aerodynamics effects there is similar behavior, where those effects are a delimitation of them for each axis, in that sense it just need a different develop of function, at this case in denied to just include those effects that are part of this investigation, other effects would be studied at future works.

4.3.2 Translation Dynamics

It was mentioned before position dynamics of the aircraft system, where equation 4.12 introduce those inertial forces, for illustrative purpose are shown below:

$$F_I = mge_3 + D_\xi$$

On the other hand, there is the body frame, for this case are introduce newer terms that are related to the tilting mechanism that introduces an external frame, mentioned before, which for our case is the tilting-rotor frame (Figure 4.3), for that reason is develop forces for that frame before implementing them into body frame, that would allow us to produce those thrust vector definition for position dynamics. For the tilting-rotor frame (defined as R frame), the thrust force is aligned with

negative z_R, such as the force vector in this frame is defined as:

$$\begin{bmatrix} F_{R_x} \\ F_{R_y} \\ F_{R_z} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ -F_{1,2} \end{bmatrix} \tag{4.21}$$

Translating to the body frame notation →

$$\begin{bmatrix} F_{x_B} \\ F_{y_B} \\ F_{z_B} \end{bmatrix} = \begin{bmatrix} 0 & 0 & \sin(\delta_R) \\ 0 & 1 & 0 \\ 0 & 0 & \cos(\delta_R) \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ -F_{1,2} \end{bmatrix} \tag{4.22}$$

It should be noted that equation 4.22 is only representative not the complete body forces vector, which would be developed below. To summarize, it could be represented by terms illustrated in equation 4.22 in the compact form such as:

$$F_{x_B} = -F_{1,2} \sin(\delta_{R_{1,2}}) \tag{4.23}$$

$$F_{z_B} = -F_{1,2} \cos(\delta_{R_{1,2}}) \tag{4.24}$$

Making the consideration that F_3, and F_4 are static rotors, it could develop the complete body forces vector, which results on:

$$\begin{bmatrix} F_{x_B} \\ F_{y_B} \\ F_{z_B} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ -F_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -F_4 \end{bmatrix} + \begin{bmatrix} -F_1 \sin(\delta_{R_1}) \\ 0 \\ -F_1 \cos(\delta_{R_1}) \end{bmatrix} + \begin{bmatrix} -F_2 \sin(\delta_{R_2}) \\ 0 \\ -F_2 \cos(\delta_{R_2}) \end{bmatrix} \tag{4.25}$$

At compact for is expressed as:

$$F_B = -F_3 e_3 - F_4 e_3 + R_{\delta_1} F_{R_1} + R_{\delta_2} F_{R_2} \tag{4.26}$$

For further definitions of torques, rotor body forces can be expressed as:

$$F_{BR_1} = R_{\delta_1} F_{R_1} \tag{4.27}$$

$$F_{BR_2} = R_{\delta_2} F_{R_2} \tag{4.28}$$

Resulting in a complete expression of:

$$F_B = -F_3 e_3 - F_4 e_3 + F_{B_{R_1}} + F_{B_{R_2}} \tag{4.29}$$

If rotor vector F_{B_R} are solved, they result on:

$$\begin{bmatrix} F_{B_{R_{x_1}}} \\ F_{B_{R_{y_1}}} \\ F_{B_{R_{z_1}}} \end{bmatrix} = \begin{bmatrix} -F_1 \sin(\delta_{R_1}) \\ 0 \\ -F_1 \cos(\delta_{R_1}) \end{bmatrix} \tag{4.30}$$

$$\begin{bmatrix} F_{B_{R_{x_2}}} \\ F_{B_{R_{y_2}}} \\ F_{B_{R_{z_2}}} \end{bmatrix} = \begin{bmatrix} -F_2 \sin(\delta_{R_2}) \\ 0 \\ -F_2 \cos(\delta_{R_2}) \end{bmatrix} \tag{4.31}$$

Is also important to mention that forces are produced by rotating propellers, so they are defined as:

$$F_k = C_{T_a} \omega_k^2 \tag{4.32}$$

Another element to define is related to the aerodynamic thrust vector, which in this case includes the components due to frontal rotors change as expressed below:

$$T_T = \begin{pmatrix} 0 \\ 0 \\ F_1 \sin(\delta_1) + F_2 \sin(\delta_2) + F_3 + F_4 \end{pmatrix} \tag{4.33}$$

With that definition is possible to develop position terms, which were already presented in the last system, for this case is re-write to relate to this system.

$$\dot{\xi} = V$$

$$m\dot{V} = R(-T_T) + mge_3 + D_\xi$$

Including D_ξ which is related to aerodynamic effects, such as lift, which in the final configuration would be an important part of this describing equations.

4.4 Tilt-rotor with fixed wing

This configuration is related to the last one presented, there are slight changes in configurations, but in the analytical field there is content at those design variables, by that reason, this configuration uses the terms of tilting-rotor configuration presented before, it is a part of the system that was isolated to evaluate dynamics, which for that case of equations of motion it is just necessary to implement those newer dynamics on the existing model, for visualization purposes it would be re-write them to this section but is important to realize that relation.

Before equation development, is important to define the rigid body of this system, locations of forces, the center of mass, and axes, as shown in Figure 4.6.

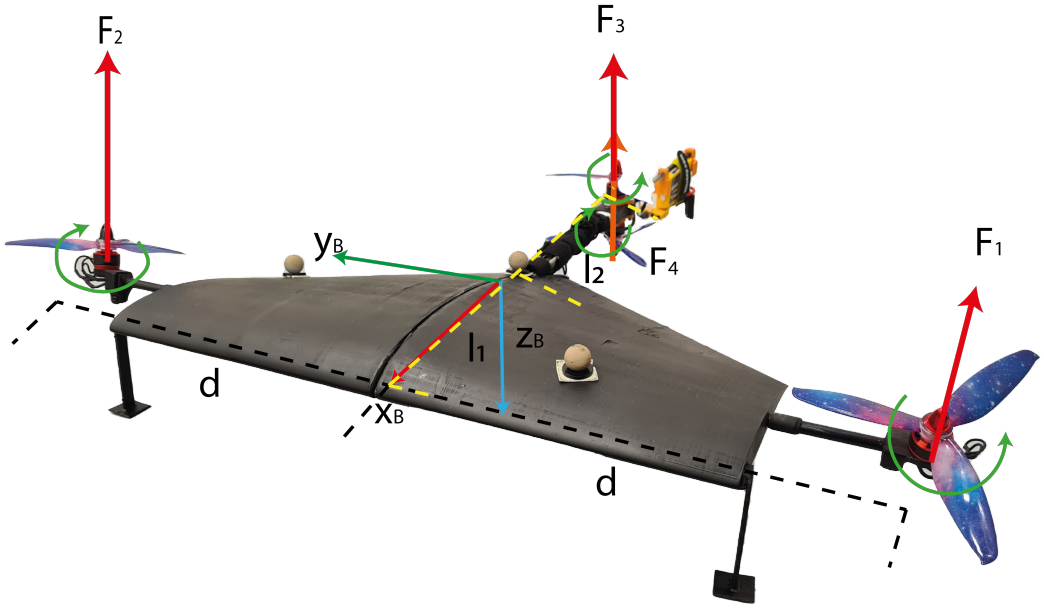


Figure 4.6: Tilting-rotor with fixed wing prototype Forces directions.

Once is defined is possible to develop orientation and position dynamics, with special detail on aerodynamics, the part where is introduce the fixed-wing interaction with the entire system already defined in the second prototype.

4.4.1 Attitude Dynamics

As the final prototype is would be defined as the system with all its structure, even if it shared components with other prototypes, that reason is analyzed the system from a generic form, where equations4.34 and 4.35 presented angular speeds, and torque interactions respectively highlighting that it represents the relation between the body frame and Euler angles at the inertial frame, with those considerations is possible to establish:

$$\dot{R} = R\hat{\Omega} \tag{4.34}$$

$$J\dot{\Omega} = -\Omega \times J\Omega + \tau_a + D_\eta \tag{4.35}$$

Where $\hat{\Omega}$ is already defined in equation 4.6, which is used as the same parameters for this system in terms of pqr angular velocities.

$$\tau_a = \begin{pmatrix} \tau_\phi \\ \tau_\theta \\ \tau_\psi \end{pmatrix} = \begin{pmatrix} d(f_1 - f_2) \\ l_2(f_3 + f_4) - l_1(f_1 + f_2) - \frac{1}{4}c\mathcal{L}_\alpha \\ Q_1 + Q_3 - Q_2 - Q_4 + f_1\sin(\delta_{R_1}) - f_2\sin(\delta_{R_2}) \end{pmatrix} \tag{4.36}$$

Where c is the mean aerodynamics chord and $\mathcal{L}$ lift force that also induce a momentum dependent on α angle of attack, other elements are already defined for tilting-rotor configuration.

4.4.2 Translation Dynamics

The main core of a system that has motion is based on its orientation and position capabilities, for this section seconds are explained for this specific system, resulting in an angular motion characterization that allows us to orientate forces and linear actuation to control them to use it on a delimited space, at this case earth, becoming possible to flight.

This system has a huge quantity of forces that interact with it, as a simplified for

those are grouped in the following equation:

$$F_I = mge_3 + D_\xi \tag{4.37}$$

In this case, are included body frame forces and external forces, for this specific prototype both are important, to have a correct interaction of the fixed wing with the actuator system. For that reason, are defined both groups of forces.

$$\begin{bmatrix} F_{x_B} \\ F_{y_B} \\ F_{z_B} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ -F_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -F_4 \end{bmatrix} + \begin{bmatrix} -F_1 \sin(\delta_{R_1}) \\ 0 \\ -F_1 \cos(\delta_{R_1}) \end{bmatrix} + \begin{bmatrix} -F_2 \sin(\delta_{R_2}) \\ 0 \\ -F_2 \cos(\delta_{R_2}) \end{bmatrix} \tag{4.38}$$

$$T_T = \begin{pmatrix} 0 \\ 0 \\ F_1 \sin(\delta_1) + F_2 \sin(\delta_2) + F_3 + F_4 \end{pmatrix} \tag{4.39}$$

For external forces, ar include specially aerodynamics ones, defining them as:

$$D_\xi = \begin{pmatrix} d_{\xi_1]} \\ d_{\xi_2]} \\ d_{\xi_3]} \end{pmatrix} = RW^T \begin{pmatrix} D_a \\ Y_a \\ L_a \end{pmatrix} \tag{4.40}$$

Internal forces that are important to analyze our Lift and Drag, already seen at in the last equation, are developed below, to maximize the parameters that are induced in this system.

$$L = \frac{C_l \rho v^2 A}{2} \tag{4.41}$$

$$D = \frac{C_d \rho v^2 A}{2} \tag{4.42}$$

And as final position dynamics, is possible to introduce those dynamics mentioned before into the next equations, which group the entire system into generic terms, to describe motion in terms of position, with the entire system forces interaction.

$$\dot{\xi} = V \tag{4.43}$$

$$m\dot{V} = R(-T_T) + mge_3 + D_\xi \tag{4.44}$$

Chapter 5

Avionics

Avionics term results from a combination of aviation and electronics [35], which are the components used in aircraft, not just electronics, other elements are also included, but for this case, it is only analyzed microcontroller unit (MCU) and Inertial Motion Unit (IMU), especially for signal processing purposes.

The importance of avionics is related to the whole control of aircraft, those units estimate the states for their location in references with it, as well as using external references for spatial location, that give feedback to the flight control that chose the filtered output signals to perform a stable flight, in that sense these parts have the mathematical part, real-world sensing, and output, making an interrelation of all of them, that becomes into the heart part of our system.

An Attitude and Heading Reference System (AHRS) provides orientation information of an object such as a UAV by fusing sensor data from IMU [36], for this application, there are some requirements for the system raw data from the IMU and processing of that data, were is include data acquisition and filtering; if we have appropriate data is possible to develop an AHRS using a fusion algorithm that estimates Euler angles, for this application it is used that methodology.

5.1 Signal Processing

Signal acquisition on sensors depends on their manufacture and operation, internally it makes sensing of the physical phenom, and it transmits that signal [42]; there are different types of outputs, typically analog and digital, there is used for interpretation on MCU, in terms of protocols it should be compatible to have a correct communication and especially adequate data. Data acquisition is a complete research topic, in this work it would not be expanded just clarify that it is use digital communication, in that sense data is already collected and pre-filtered by the manufacturer system, this has also limitations, refresh rate is limited and it must be a synchronous system, making a complex system to develop at control field.

Acquired data is named "raw data" due to its nature of not previous interpretation, and for that reason is requeried a filter process, adequacy, and fusion in case of complex signals; those processes are part of signal processing, for this case filter and fusion are used.

The first point to consider for IMU data is that it needs to be scaled from bit data to physic data, accelerometer data is divided by the resolution expected and its sensibility, and gyroscope adequacy uses the same methodology; in this case, 16 bits resolution is used, at this point is considered raw data, that should be filtered to use at AHRS process.

For this case, it is used first order filter for the accelerometer, at low pass filter configuration, and the second order filter for the gyroscope.

The methodology used for this data process is shown in Figure 5.1, the conceptual diagram shows the filter and fusion process implemented.

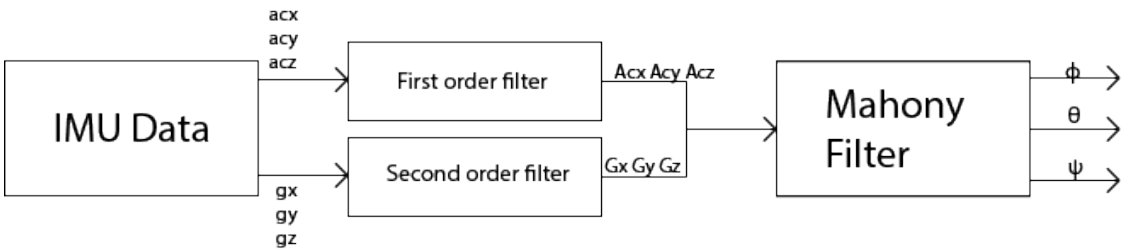


Figure 5.1: Diagram of signal processing for attitude estimation.

5.1.1 Filtering

The filtering process is a signal processing process that allows us to separate, correct, adequate, and clean data from raw, in terms of continuous signals, it is possible to select some frequency to mitigate, those could be low o high frequency, also is possible to mix those process to focus on specifics bandwith; at IMU signals there are to different kind of signals, from accelerometers there are the low-frequency signals, and from the gyroscope, those are high-frequency signals, in that sense, they need a different kind of filter.

Another classification of filters is based on their nature, they could be analog or digital, using physical components such as capacitors and inductors for passive analog ones, and signal processing by equations in a digital field made by a microcontroller; is important to mention that filters are not necessarily an ideal element, it has its consequence, most commons are signal mitigation and delay.

At the accelerometer it is used a low pass filter, this signal would be conditioned by a first-order filter, due to the importance of that signal at the fusion filter, this one is not used as wide as the gyroscope, allowing signal noise. For this type of signal is important to identify frequency-cut, parameters to filter unrecognized signals, also in the case of periodic noise it could be also filtered without signal loss. For a non-extensive use of processing, it is selected first-order filter,it structure is presented in equation 5.1.

$$y = y_{n-1}(1 - \alpha) + \alpha * x \tag{5.1}$$

This filtering algorithm, uses an α gain to select dependence on last values, whereas bigger α less dependence on last values would be considered, in terms of filtering this is considered as less mitigation of signals, y as the output signal, x actual input, and y_{n-1} as previous value of the filter, this representing and numeric integration.
Equation (5.1) is used in our system to have a less noisy output, as well as mitigation of inconsistent inputs that do not represent real signals, as known accelerometer signals are used at fusion filters to mitigate gyroscope drift, also to consider those fast changes, in that sense, are used a complementary signal and fast response one, by that reason it could not be filtered aggressively [36], is selected a first order filter for this signal to guaranteed continuous signal and not been necessary a fine filter process.
On the other hand, there is the gyroscope signal, for this AHRS is highly important, a first-order filter was tested with onboard sensors and control algorithms, but this did not show acceptable results, 20dB was not a fast response for this signal, due to a noisy system, at multi-rotors are typical behavior [37], a second order filter is implemented due to its 40dB response, becoming into a desirable response were is needed it at a high filter signal, preventing delayed signals, not acceptable inputs at control field, especially at a flying system with fast dynamics.
For this case, a low-pass filter needs it, which is represented in equation 5.2, gains are selected it is known the signals to filter, design process consists of plotting the case, selecting the cut-off point, and selecting a determined change behavior, with those values selected the gains and order used for a filter, at unknown system is also possible to use empirical selecting process, using literature and experimental test for selection; at UAVs a second order is enough to have desirable signals and well-implemented inputs for control purpose, remembering that those signals are the center of feedback for our system, in that sense, better inputs of angle estimations would be directly related to a better system response against real-world conditions.

Equation 5.2 is presented as the algorithm for gyroscope MEMS.

$$y = \omega_n^2 x - 2\xi\omega_n \dot{y_{n-1}} - \omega_n^2 y_{n-1} \tag{5.2}$$

The main objective of this second-order filter is to use more terms for filtering, including other states and other aspects, making that adhesion possible to have a faster filter but with other considerations, not mentioned in this work, for simplification purposes. Elements use are two gains, derivative terms, and previous values, those to have a filter that is affected by last values, at low-pass filters this allows mitigating unexpected signals.

5.1.2 Angular Estimations

For sensor fusion it is selected Mahony orientation filter, which is an optimal filter, with a lower execution time, in comparison with other approaches such as Kalman Extended and Madgwick [37], just a complementary filter would be faster, but it has many considerations that affect the performance of the whole system, in that sense is chosen the most balanced filter.

Mahony filter uses an estimated vector v described in equation 5.3, the quaternion and angular rate errors are given by q_e , w_e, and time difference as Δt; this algorithm uses two vector references E_a and E_m for acceleration and magnetic field respectably.

$$\hat{v} = \begin{bmatrix} \hat{v_x} & \hat{v_y} & \hat{v_z} \end{bmatrix}^T \tag{5.3}$$

For the static case it is used and non-magnetic references:

$$E_a = \begin{bmatrix} 0 & 0 & 9.8 \end{bmatrix}^T$$

$$E_m = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}^T$$

And for a noise-free environment, it is used the relation at equation 5.4, where $\bigotimes$ is the quaternion multiplication, and E_{aq} is the quaternion representation of the acceleration reference vector.

$$S_{a_q} = q^{-1} \bigotimes E_{a_q} \bigotimes q \tag{5.4}$$

where:

$$S_{a_q} = \begin{bmatrix} 0 & S_{a_x} & S_{a_y} & S_{a_z} \end{bmatrix}^T$$

On the other hand, there is the kinematic equation of the rigid body, given by the angular velocity measurements from the gyroscope, its objective is to describe variations of the attitude in terms of quaternions such as:

$$\dot{q} = \frac{1}{2} q \bigotimes S_{w_q} \tag{5.5}$$

Those definitions allow us to consider the measurements from our sensors as adequate to math terms, but the main Mahony filter computes the system according to algorithm 1.

Algorithm 1: Mahony Filter

$s_{\hat{a}_{q,t}} = \hat{q}_{t-1}^{-1} \bigotimes E_{a_{q,t}} \bigotimes \hat{q}_{t-1}$

$s_{\hat{m}_{q,t}} = \hat{q}_{t-1}^{-1} \bigotimes E_{m_{q,t}} \bigotimes \hat{q}_{t-1}$

$s_{w_{mest,t}} = [s_{a_t} \times s_{\hat{a}_t}] + [s_{m_t} \times s_{\hat{m}_t}]$

$s_{\dot{\hat{w}}_{b,t}} = -k_i s_{w_{mes,t}}$

$s_{\hat{w}_{r,q,t}} = s_{w_{q,t}} - \begin{bmatrix} 0 & s_{\hat{w}_{b,t}} \end{bmatrix} + \begin{bmatrix} 0 & k_p s_{w_{mes,t}} \end{bmatrix}$

$\dot{\hat{q}} = \frac{1}{2} \hat{q}_{t-1} \bigotimes s_{\hat{w}_{r,q,t}}$

A summary of that algorithm, is computed the error by cross-multiplying measurements by the sensors, and the estimated vectors as well as acceleration and magnetic fields are cross-multiplied by its estimations, this method allows us to correct the gyroscope bias [38].

As the output is shown the quaternion q, but for our application it is used Euler representation, becoming necessary a transformation, consider the quaternion as shown

in equation 5.6, it would be using the transformation given in equations 5.7.

$$q = \begin{bmatrix} q_w & q_x & q_y & q_z \end{bmatrix} \tag{5.6}$$

And the transformation is:

$$\begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix} = \begin{bmatrix} \arctan(\dfrac{2(q_w q_x + q_y q_z)}{1 - 2(q_x^2 + q_y^2)}) \\ \arcsin(2(q_w q_y - q_z q_x)) \\ \arctan \dfrac{2(q_w q_z + q_x q_y)}{1 - 2(q_y^2 + q_z^2)} \end{bmatrix} \tag{5.7}$$

For computational purposes, it is used atan2 due to limitations on code implementations where it only considers a range from $\frac{-\pi}{2}$ to $\frac{\pi}{2}$, and that change allows us to use the whole spectrum.

In summary, it is used the methodology presented in Figure 5.2 for AHRS, the central part of the reference for our system, becomes the main loop feedback, due to that reason is paid special attention on this scope, empirically is demonstrated in the validation field that references signals are the main part of robustness of that kind of systems.

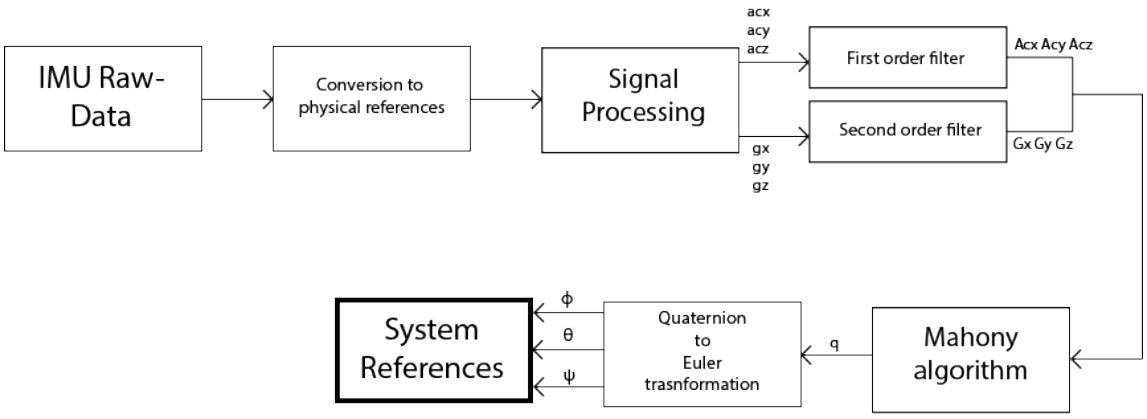


Figure 5.2: Diagram of AHRS implementation.

Chapter 6

Guidance and Navigation Control Algorithms

An important topic to study in vehicles is related to their capabilities to move in a determinate space, their behavior, and algorithms to perform those movements, becoming into a guidance and navigation control, which is an algorithm that includes those aspects of a vehicle to be able to perform those actions. Those kinds of algorithms group the navigation and attitude controller, as well as characteristics of the vehicle use, named translation, and attitude dynamics, with that whole data, is possible to have a reference point o trajectory and with all of those elements, the system would adopt that command converting that reference into inputs that create the motion desired to accomplish that.

This system could be an open or closed loop, last one tends to be more precise thanks to its feedback node that allow correcting undesired behaviors and performs an optimal accomplish of navigation, the behaviors are related to nonideal conditions, and with the feedback node is possible to deny those disturbances.

For our specific implementations, it is proposed the algorithm presented in the diagram of Figure 6.1, including those parameters already mentioned in section 4, and newer elements as external references, which allow us to have more data for a precise accomplishment of our trajectory.

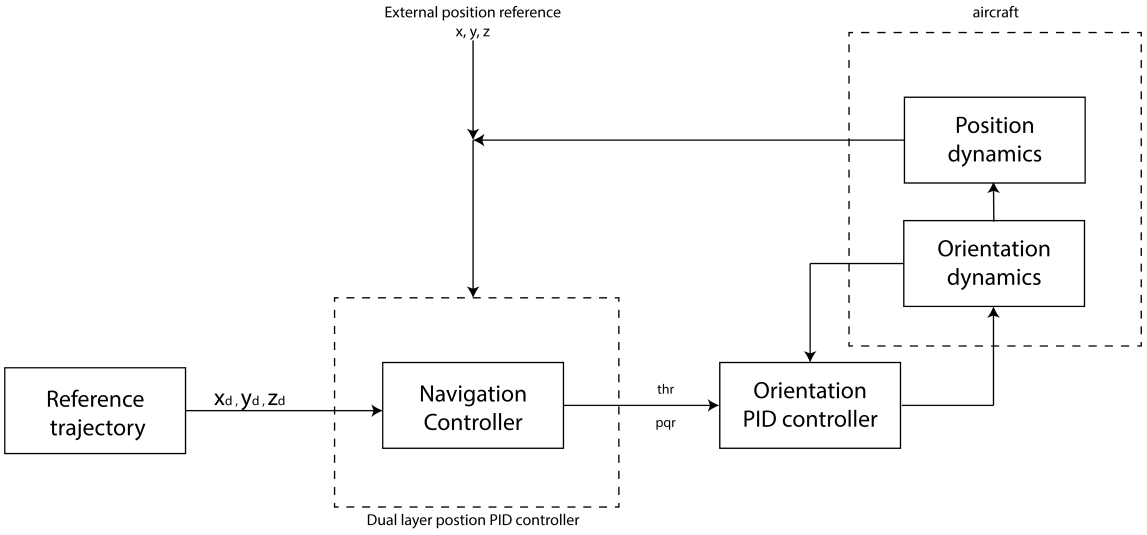


Figure 6.1: Guidance Navigation and Controller algorithm use at implementation.

This algorithm is based on a group of systems that feed consecutively, getting as input a reference, which could be a point or a trajectory, for practical purposes it would use trajectory as the main point of input even-thought is possible the other input; this algorithm is dived into 2 main systems, navigation, and orientation controller, other elements are used for feedback on both systems, dynamics for orientation, and position references for navigation.

Principally, the algorithm is based on different PID controllers, in this case, are not the main point of the study, for that reason are not explained thoroughly.

Control laws are required to define elements, especially those interactions on the systems that allow the accomplishment of reference trajectory, in that sense, a guidance and navigation structure for a basic actuation output declaration.

To create a structure that allows us to have parameters as inputs, there are redefined equations 4.4, 4.5, 4.15, and 4.16, getting as simplified equations:

$$\dot{\xi} = V \tag{6.1}$$

$$\dot{V} = u_p + d_\xi \tag{6.2}$$

$$\dot{R} = R\Omega \tag{6.3}$$

$$\dot{\Omega} = u_a + d_R \tag{6.4}$$

It introduced terms for those equations that are important for the system declaration, most of them inputs and signals that would allow navigation, those are enlisted below:

- u_p = position virtual control input defined as:

$$u_p = ge_3 + \frac{(Re_3)TT}{m} \tag{6.5}$$

- u_a = orientation virtual control input, which is:

$$u_a = \frac{\tau_a}{J} \tag{6.6}$$

- d_ξ = external forces that interact directly with the aircraft body, in this case it is used as aerodynamics forces input for our cases that are required. (Also use as $D\xi$)

- d_R =torque perturbations and some elements as gyroscopic effects are introduced in these terms. ($J\dot{\Omega} = -\Omega \times J\Omega + D_\eta$)

For guidance is required an approximation that allows us to go from internal control terms of our system (guidance and orientation of the aircraft), that is rotation matrix that would have as result a guidance frame defined in a Euclidean space $\mathbb{R}^{\mathbb{F}}$, with this structure the controller would be capable of taking the real rotational matrix to the aircraft, which would get as input just the parameters allow by its internal control algorithm. The guidance frame is defined as three vectors dependent on trajectory and aircraft dynamics, getting the next expression.

$$\mathcal{G} = \{f_g, b_g, n_g\} \tag{6.7}$$

Defining those vectors:

- n_g is a normal control vector, which is defined in base to an established direction by the position control components

$$n_g = \frac{ge_3 + u_p}{||ge_3 + u_p||} \tag{6.8}$$

- f_g forward vector, orthogonal vector of n_g, defined as:

$$f_g = \frac{ng \times e_1}{||n_g \times e_1||} \tag{6.9}$$

- b_g = bi-normal vector, orthogonal to both previous vectors

$$b_g = -(f_g \times n_g) \tag{6.10}$$

Those vectors allow to have a guidance frame, which represents rotation elements of the aircraft to accomplish the desired trajectory, where it must guarantee u_p, creating the rotational matrix:

$$R_d = \begin{bmatrix} f_g & b_g & n_g \end{bmatrix} \tag{6.11}$$

Having the guidance frame is possible to establish a control approach that allows us to introduce u_p as input, and position references as feedback, which would allow us to have a complete scheme to have navigation, at this case it is proposed a classical Proportional, Integral, and Derivative (PID) scheme; is possible to have a complete scheme of navigation with that kind of control if we have correct feedback and fast enough system, by that reason is used the following PID saturated structure [45].

$$F_{x_d}^{sat} = \text{Sat}\left(k_{p_x}\tilde{x} + k_{dx}\dot{\tilde{x}} + k_{ix}\int \tilde{x}dt\right) \tag{6.12}$$

$$F_{y_d}^{sat} = \text{Sat}\left(k_{p_y}\tilde{y} + k_{dy}\dot{\tilde{y}} + k_{iy}\int \tilde{y}dt\right) \tag{6.13}$$

$$\tag{6.14}$$

Defining errors as:

$$\tilde{x} = x_d - x \tag{6.15}$$

$$\tilde{y} = y_d - y \tag{6.16}$$

That structure is based on absolute values, but for our case, it was proposed a reference vector ξ , in that sense is redefine the previous structure into:

$$F_{\xi_d}^{sat} = \text{Sat}\left(k_{p_\xi}\tilde{\xi} + k_{d\xi}\dot{\tilde{\xi}} + k_{i\xi}\int \tilde{\xi}dt\right) \tag{6.17}$$

And error to:

$$e_{\xi} = \xi_d - \xi \tag{6.18}$$

$$\dot{\xi} = \dot{\xi_d} - \dot{\xi} \tag{6.19}$$

Where ξ_d is the navigation reference and $\dot{\xi_d}$ is temporal derivative.

For better performance of navigation and attitude, it used dual layer controllers, using as the first layer a rate control of the system, velocity for those cases, and a second layer for position and angular respectively, nesting both layers it has a final output; dual layer controllers use the same structure as presented before, it just feeds one to the other by that reason is not presented as equations, just mentioned.

Chapter 7

Real-Time Validation

As validation it develops a design of experiments (DoE) that allow us to test the capabilities of our systems; experiments selected are tracking missions, which allow us to verify its performance with similar patterns and create combinations of movements, taking into account that every system would perform better at those missions which were considered at the design process, for this convertible case it is performing a kind of missions that allow us to test the system on different scenarios are not considered a convertible mission due to limitations on tracking position.
As test platforms, it was selected the quadrotor prototype as well as the fixed-wing Tricopter, excluding the one without a wing for simplification of results it was also used for dynamics analysis which was useful for the final prototype. Platforms used are presented in Figure 7.1, using the same avionics, propulsion, and power modules..

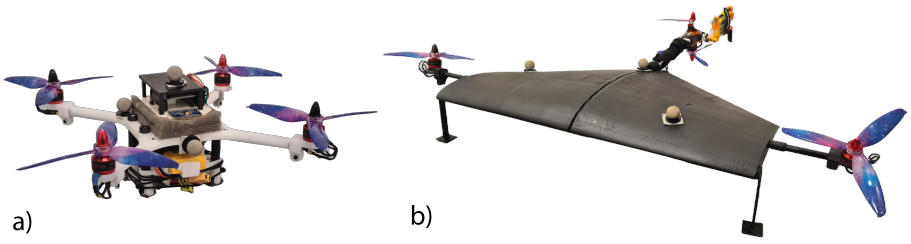


Figure 7.1: Platforms use for experiments, a) Conventional quadrotor, b) Convertible Tricopter.

The tracking platform used is the VICON system provided by the Navigation Laboratory, at Facultad de Ingenieria Mecanica y Electrica from Universidad Autonoma de Nuevo Leon; this is a laboratory integrated by a system of 16 $VICON$ $T-40$ cameras, which use optical markers at each object for motion capture, that information is processed at a ground station and use it for general angular and linear position states estimation.
For position control, it is using an external computer to compute the algorithm previously proposed, using as protocol UDP communication over LAN, wired connection for tracking, and WIFI for aircraft communication, some characteristics of this computer are enlisted below.

- Processor: Intel Core i7 9750H (6 logical, 12 threads)
- Physical Memory: 24GB
- LAN adapter: Realtek GbE (Low latency)
- LAN2 adapter: Intel AC (MIMO)

For control, interface and data recording were use NI-LabVIEW 2021 64-bits, uses its parallel processing paradigm, optimizing data processing and no dependence on the separated process, by that reason is important the use of a computer with multiple cores and multiple networks adapters.
Considering two types of aircraft that perform different missions, it was designed general tests as well as specifics for each one, its general description is performed in Table 7.1, and for specifics values, it would be developed each experiment into a separate section.

Experiment	Platform	Description
Circle	Quadrotor, Convertible Tricopter	Circle pattern with tangent tracking, fixed Z, and multiple experiments development for dependence on velocity analyze
Ellipse	Convertible Tricopter	Modification of circle pattern with a wider semi-linear segment for forwarding flight test as well as reaction to fast changed pattern
Infinite	Quadrotor, Convertible Tricopter	Complex pattern for whole system test, combined capabilities are test
Point tracking	Convertible Tricopter	Test of linear motion, damping effects, and height stability due to fast changes
Hover	Quadrotor, Convertible Tricopter	Taking-off and landing process of aircraft and drift analyze
Spiral	Quadrotor	Circle pattern with variable Z
Tilting Ramp	Convertible Tricopter	Tilting rotor test for control test, where required an input similar to a forward flight with a process of stopping at the end of the path
Fast line	Convertible Tricopter	Test for max linear velocity on controlled environmental

Table 7.1: Design of experiments for Quadrotor and Convertible Tricopter Aircraft.

As a complete DoE, it was performed 120 experiments, repeating each kind of experiment a couple of times for covariance analysis, but since this work become extended it was reduced as an experiment for specimens with variance at those that showed velocity dependence.

7.1 Quadrotor

For a conventional aircraft are desired paths based on missions that include interior navigation, where its high maneuverability is desirable, by that reason selected those paths mentioned in Table 7.1, are expanded, and some variations are use, except at hover where use the same principle.
For the circle path use the following path parameters:

Experiment	Velocity (rev/s)	Radius(mm)
1	0.03	1500
2	0.05	1500
3	0.07	1500

Table 7.2: Circle path for conventional aircraft.

The second group of experiments is related to infinite, a complex path that is made with two groups of circles, for this case circles of 1500mm of radius, which in real trajectory is performed on an area of 6000mm x 3000mm, where at x direction is placed just de circle maximum length, but at Y it is contended the two mixed circles that create this geometry; for this platform, it used 2 test, with a variation on velocity. 0.03rev/s and 0.05 rev/s, those selected due to performance design, for our analysis are not intended higher speeds at this platform.
To test a complex path is proposed a spiral, defined as a circular pattern with variable z, decrement for this case, results of this experiments are intended for demonstration of non Z dependence and 3D path following capabilities, using the same base parameters as other experiments, are selected a radius of 1500mm, velocity of 0.05rev/s for XY plane and in this case variable z, with a decrement of 0.05m/s. As the last experiment, it is analyzed a hover, where X, Y, and Z stays constant, excluding the take-off and landing process, with this experiment analyzing the drift and small movements performance from the prototype.

For data analysis are plot some variables, in this case, are separated into 3 groups, trajectory tracking, control signals, and angular errors; the first group plot a combination of XYZ signals, real vs ideas, XY plot, and individual X vs time, Y vs time and Z vs time; on control group are analyze pqr at same graph, and angular velocities on other; as a final group is shown the angular signals, real vs ideal, those at separate plots, orientation is analyzed at this point.

7.1.1 Circle Path

Experiments enlisted in Table 7.2, are developed below, with the information mentioned before.

7.1.1.1 Experiment 1: 0.03rev/s

As the first experiment is test a circle of 1500mm of radius, 0.03 rev/s, and height of 1800mm (Fixed Z), this test shows aircraft performance on low-speed paths; from the section of trajectory is shown a couple of behaviors, this path is accomplished with an error in the range of 50mm in average, seen at Figures 7.2 and 7.3 where the path is shown at real planes. From an error perspective, seen in Figure 7.4 each axis has similar behaviors.

-Trajectory:

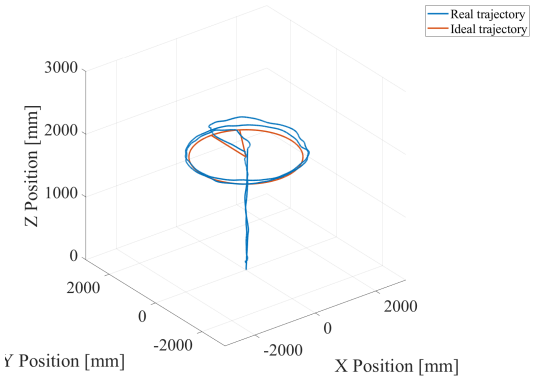


Figure 7.2: XYZ trajectory tracking, real vs ideal.

At XY visualization (Figure 7.45) is shown a more clear visualization of the experiment, showing an area of deviation of trajectory, but it still has a correct tracking of them, is also important to mention that in this case, it involves some other elements as environmental wind gust (air condition), also a variation on tracking signals as others un tracked behaviors.

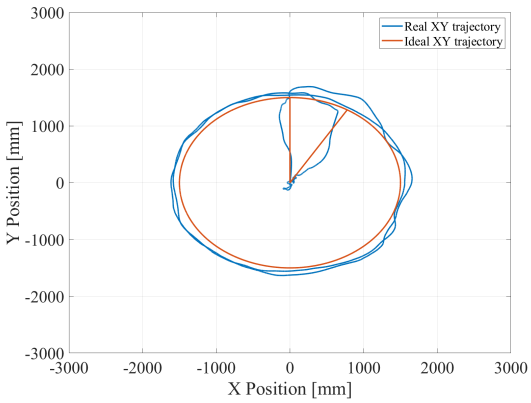
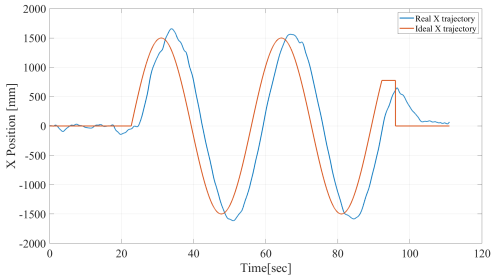
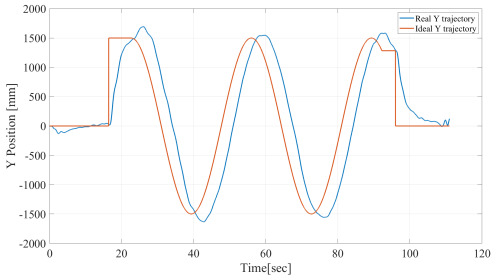


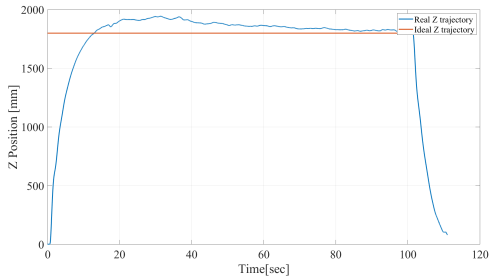
Figure 7.3: XY trajectory tracking, real vs ideal.



(a) X trajectory tracking, real vs ideal.



(b) Y trajectory tracking, real vs ideal.



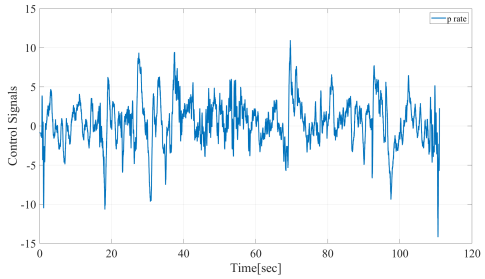
(c) Z trajectory tracking, real vs ideal.

Figure 7.4: X-Y-Z vs Time trajectory tracking.

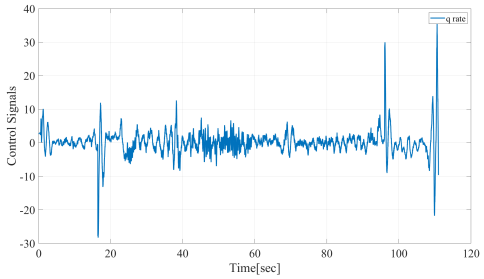
This trajectory allows us to analyze the aircraft at low-speed trajectories, where the references and the real XYZ (Figure 7.4), show a delay from that signal, but that is delimited by the tracking algorithm used, for practical use are acceptable. on the other hand, this behavior is visualized in each graph, in that sense is concluded that is a system behavior that could be optimized with a better tuning process.

-Control signals

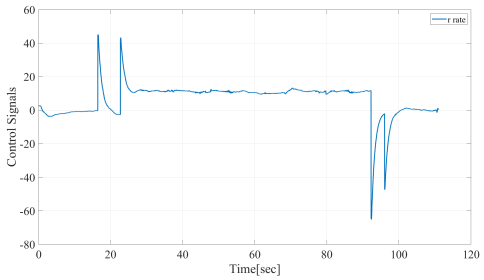
The orientation controller uses a dual layer scheme, in that sense, two types of signals are internally used by the system, attitude controller and attitude rate controller, consequently, one is feeding the other, for a description of this scheme is logged the data from the system at experiments, analyzing how internally each controller reacts across the trajectory and perturbations presented at each experiment.



(a) p rate control signal.



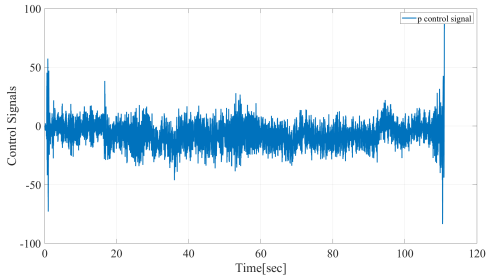
(b) q rate control signal.



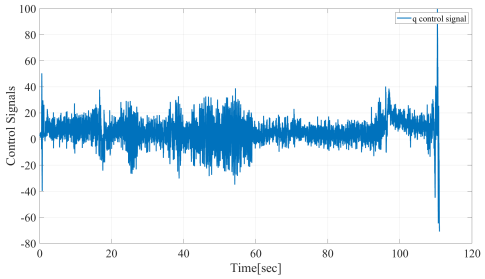
(c) r rate control signal.

Figure 7.5: Desired angular velocity p, q, r of Quadrotor Experiment 1.

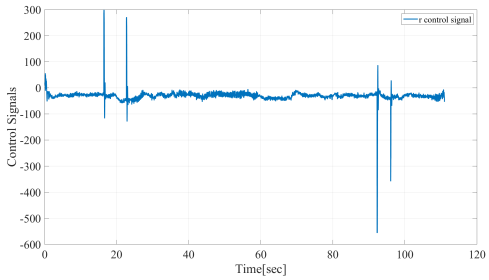
Those signals reflect as results of expected behavior, were request signals to develop angles that would reflect into linear motion for this path, also there are expected high signals request, points at that are related to perturbations or signals lost, becoming into points that this system goes to stabilization phase. A special behavior on c) is shown at this point the system is feeding it with an uncertain input or at the start and final case, are changes to zero references of yaw angle.



(a) p control signal.



(b) q control signal.



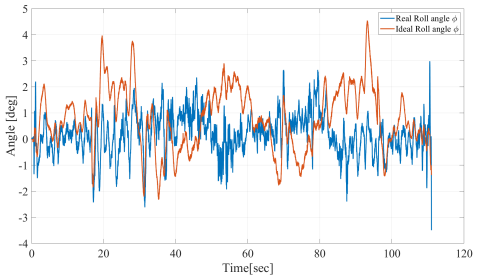
(c) r control signal.

Figure 7.6: Angular velocities Quadrotor Experiment 1.

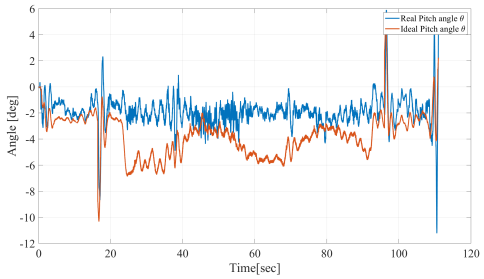
A relation between Figure 7.5 and 7.6 is evident, getting the feed response from 7.6 with more noise related as a response to the gyroscope feedback is important to mention that those graphs are scaled as maximum zoom for better visualization, but that reflects the signals as noise, which is not, according to magnitude, those signals are slight changes in comparative with the system response.

-Attitude

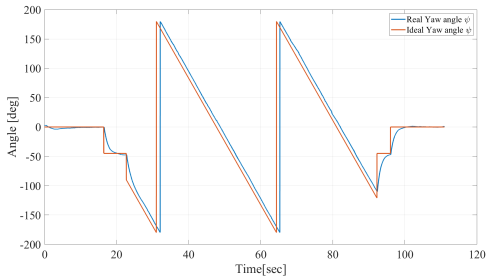
This last analysis of signals on this system is related to orientation, which directly results in control output, at this case, it is used as a performance result and follows those signals that are fed it by the positioning scheme, which in that specific case are used as deviation analyze from the ideal and real one.



(a) Roll angle.



(b) Pitch angle.



(c) Yaw angle.

Figure 7.7: Attitude angles of Quadrotor Experiment 1.

From that data is shown an important behavior where the system feeds it with references to keep path tracking, and those are followed at a maximum of 2° which in this sense are ideal results, is important to mention that those specifics cases of maximum states are also aligned with external disturbances, inducing a different behavior.

7.1.1.2 Experiment 2: 0.05rev/s

A second experiment is developed by repeating the first path changing the velocity of execution, and a radial increase of the circle following, considering this experiment as the functional tracking speed desired (0.05rad/s).

-Trajectory

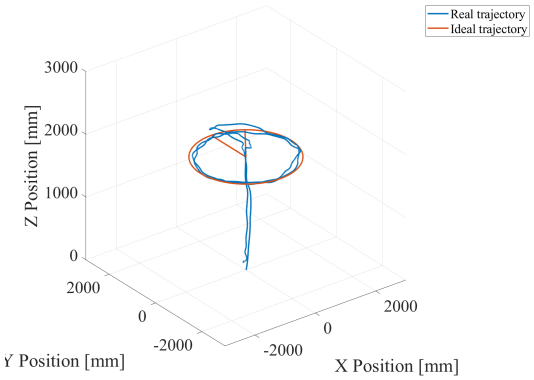


Figure 7.8: XYZ trajectory tracking, real vs ideal.

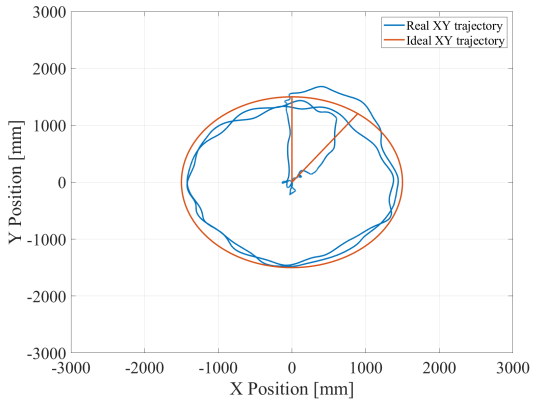
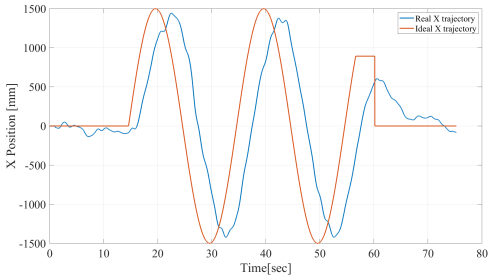
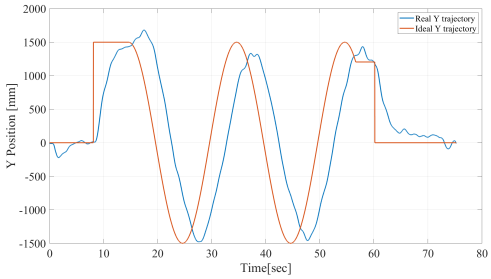


Figure 7.9: XY trajectory tracking, real vs ideal.

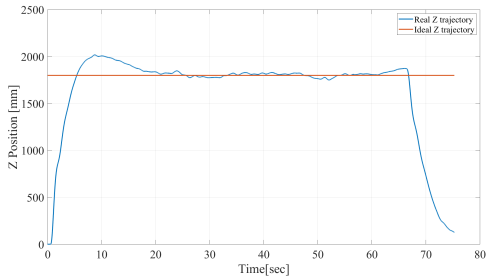
Expected results were performed by the aircraft, the path is followed with a deviation of less than the aircraft diagonal, acceptable for this kind of application, for most of the interior path tracking applications would be usable, as well as being performed with a deviation due to an expected behavior of the position control, which has gains bounded for safety purposes, tuning for more aggressive behavior is possible.



(a) X trajectory tracking, real vs ideal.



(b) Y trajectory tracking, real vs ideal.

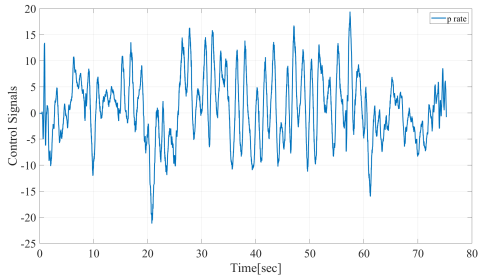


(c) Z trajectory tracking, real vs ideal.

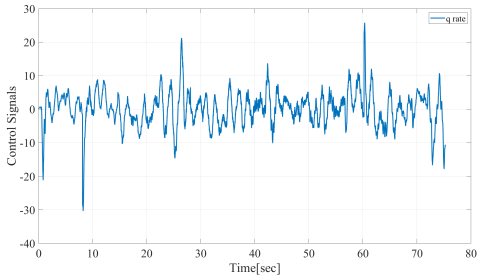
Figure 7.10: X-Y-Z vs Time trajectory tracking.

The results gap from the last graph allows us to mention that this system differs from the real signal with a small derivation in magnitude and delay, both are behaviors expected and acceptable, and characterization could be performed to mitigate them and get better performance.

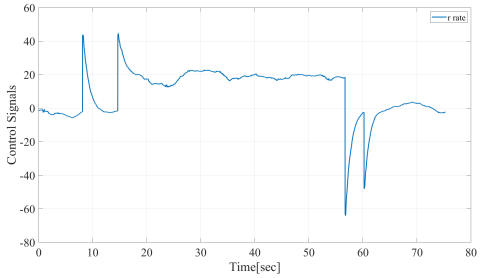
-Control Signals



(a) p rate control signal.

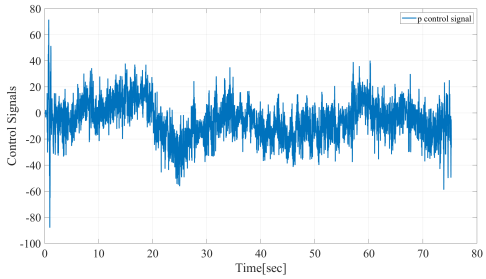


(b) q rate control signal.

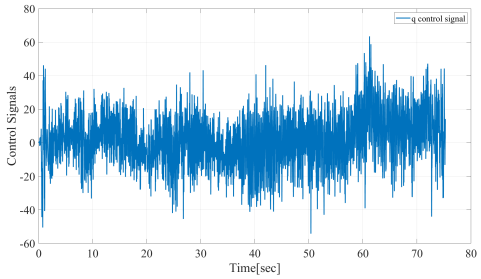


(c) r rate control signal.

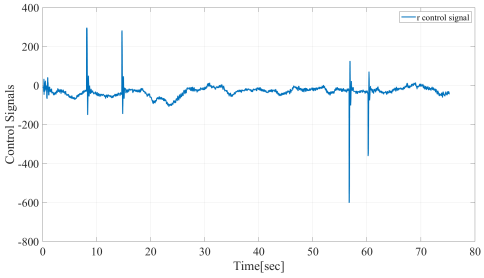
Figure 7.11: Desired angular velocity p, q, r of Quadrotor Experiment 2.



(a) p control signal.



(b) q control signal.

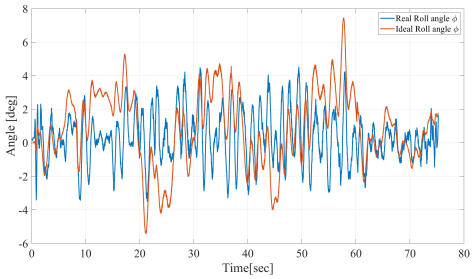


(c) r control signal.

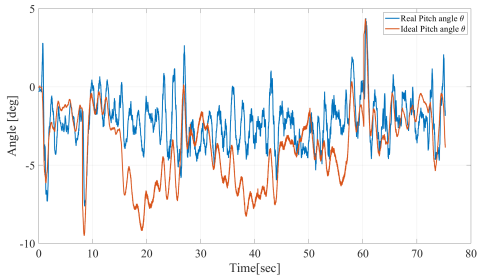
Figure 7.12: Angular velocities Quadrotor Experiment 2.

Both groups of graphs (Figures 7.11 and 7.12) show control signals that perform into a circular path with some spikes or overshoots due to perturbations, but in simple terms, those are acceptable and demonstrate similar behavior as Figures 7.5 and 7.6 in that sense are the same path with a variation on the velocity which involves more control authority but with a similar shape.

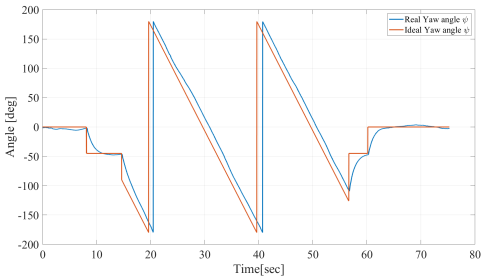
-Attitude



(a) Roll angle.



(b) Pitch angle.



(c) Yaw angle.

Figure 7.13: Attitude angles of Quadrotor Experiment 2.

At attitude angles, the system has shown differences of no more than 2° to ideal references, which allow us to have an aircraft that perform the path feed by position scheme, in that sense with these references the system develops an acceptable control.

7.1.1.3 Experiment 3: 0.07rev/s

-Trajectory

This third experiment is based on a path tracking of a circle with a higher speed, 0.07 rev/s, gyroscopic effects would be seen as well as a particular behavior of a system with a damped control scheme.

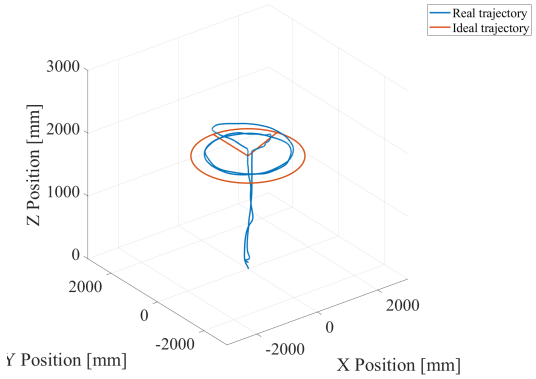


Figure 7.14: XYZ trajectory tracking, real vs ideal.

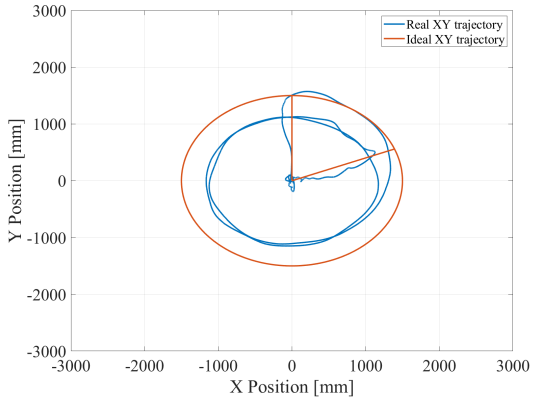
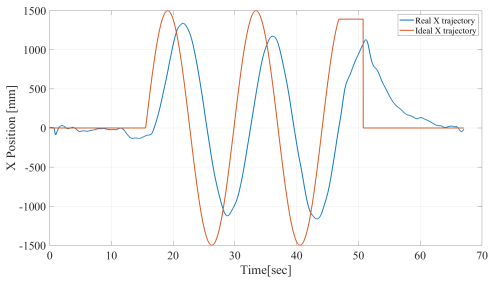


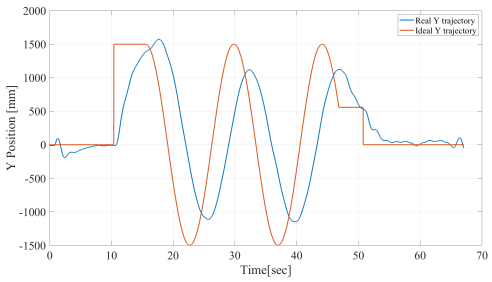
Figure 7.15: XY trajectory tracking, real vs ideal.

XYZ and XY visualization (Figures 7.14 and 7.15) allow us to make a relation between velocity and trajectory tracking, where the system tends to unperformed the trajectory and reduce it to follow references, due to a system that needs a wider control reference to follow this specific trajectory. Another point to highlight is re-

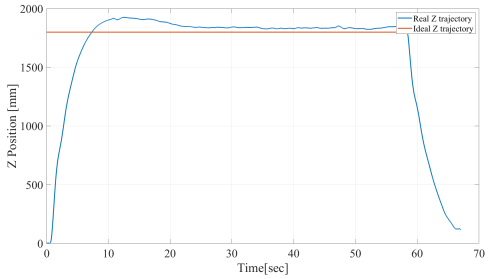
lated to precision, where the system has a tendency to deviation, but its geometrical pertinence to the original system remains still ideal for this kind of system.



(a) X trajectory tracking, real vs ideal.



(b) Y trajectory tracking, real vs ideal.

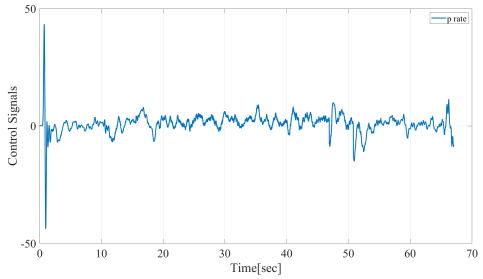


(c) Z trajectory tracking, real vs ideal.

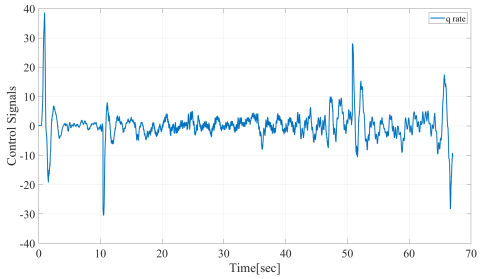
Figure 7.16: X-Y-Z vs Time trajectory tracking.

"0" phenom mentioned before is proven in figure 7.16, where individual X-Y-Z signals are visualized that each of the signals follows the geometrical shape of the system with a reduction in magnitude (for X and Y systems 7.16a and 7.16b) and delay, behaviors expected.

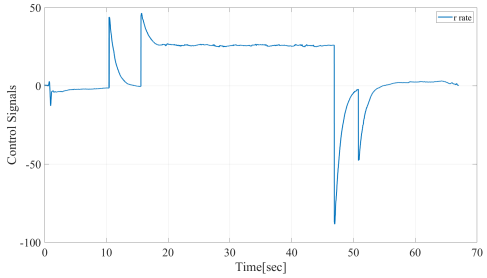
-Control signals



(a) p rate control signal.

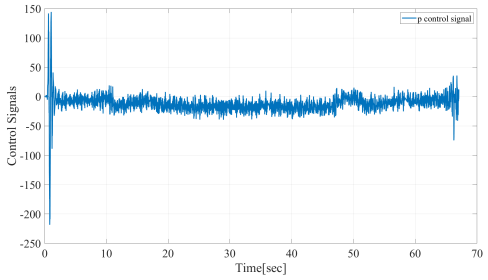


(b) q rate control signal.

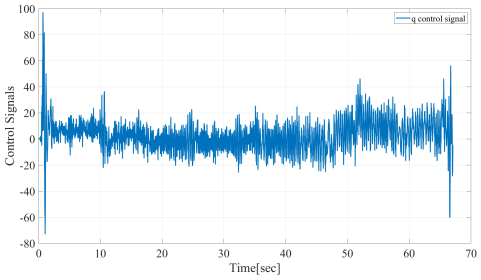


(c) r rate control signal.

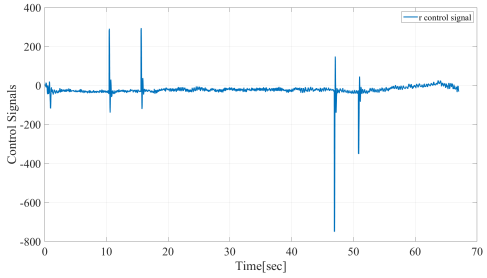
Figure 7.17: Desired angular velocity p, q, r of Quadrotor Experiment 3.



(a) p control signal.



(b) q control signal.

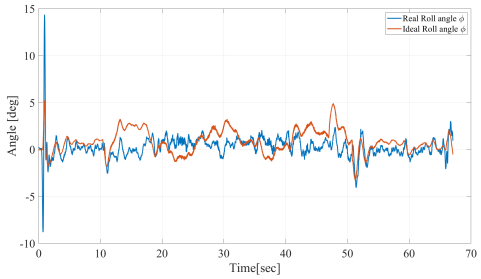


(c) r control signal.

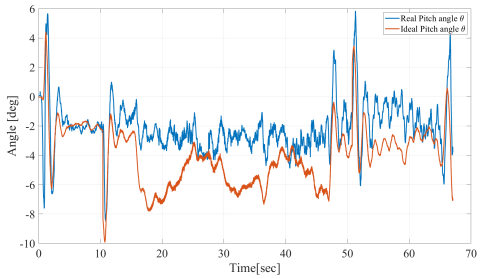
Figure 7.18: Angular velocities Quadrotor Experiment 3.

Control signals correspond to the orientation controls scheme, in this case, feed it by position control, which is the main scheme that is unperformed, for that reason the signals flatware before showed stable results with a short area of action, this due to an input that is not asking for more magnitude; isolating those signals as unique ones, showing a stable behavior.

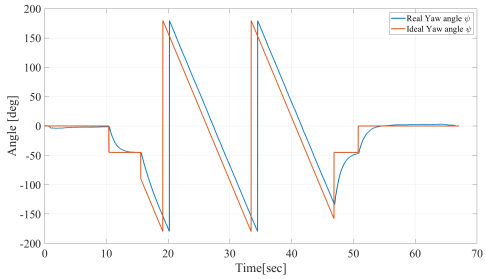
-Attitude



(a) Roll angle.



(b) Pitch angle.



(c) Yaw angle.

Figure 7.19: Attitude angles of Quadrotor Experiment 3.

For angles produce by attitude control, is shown the same behavior as in the last section, where those angles correspond to an input that is not asking for more control action; if we consider the desired input as that one needs it, it develops an acceptable mapping of them with real signal, which in short words, the system is performing what is asked by input.

7.1.2 Infinite

An infinite path is used to evaluate multiple tracking scenarios, in this case, is analyzed as a complex system that integrate linear and circular schemes; multiple velocities would be used to perform multiple experiments, seeking for deviation tendency.

7.1.2.1 Experiment 1: 0.03rev/s

-Trajectory

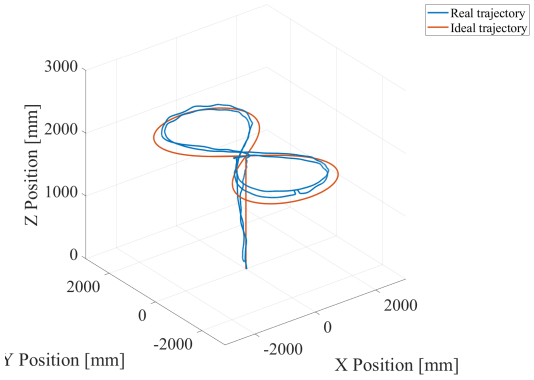


Figure 7.20: XYZ trajectory tracking, real vs ideal.

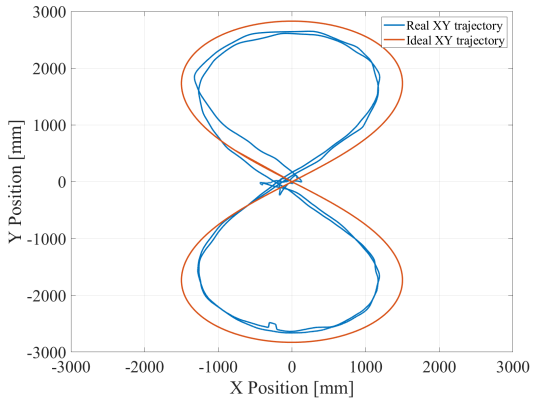
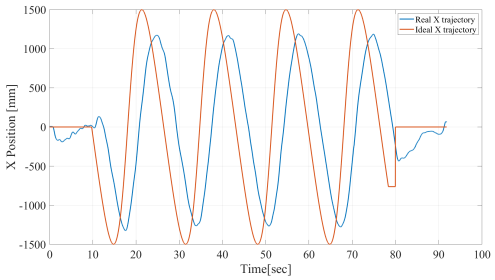
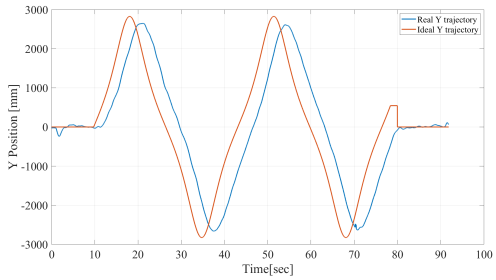


Figure 7.21: XY trajectory tracking, real vs ideal.

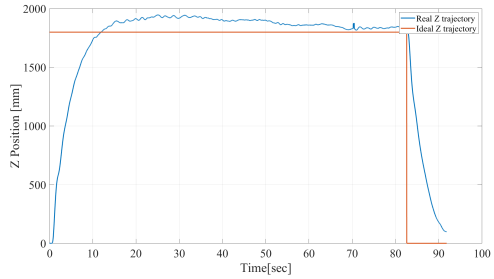
The first trajectory track, shows a deviation of the real vs ideal, reducing the magnitude, in that sense is a reduction of points developing its distance, on the other hand, it accomplishes the trajectory proposed and it showed a correct development of them, which in aircraft analyze it is ideal to demonstrate the maneuvers that the system could perform.



(a) X trajectory tracking, real vs ideal.



(b) Y trajectory tracking, real vs ideal.

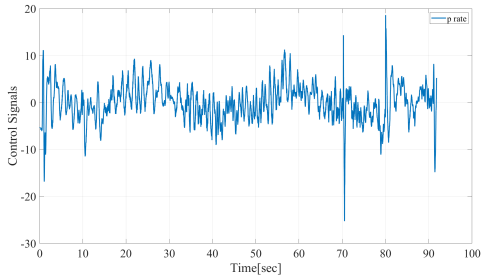


(c) Z trajectory tracking, real vs ideal.

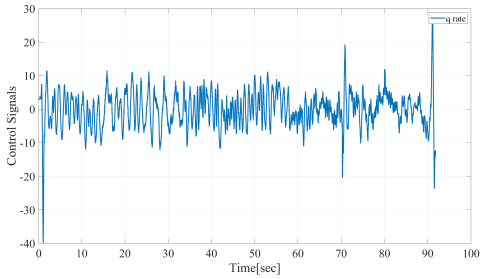
Figure 7.22: X-Y-Z vs Time trajectory tracking.

Using data from Figures 7.4, is conclude that the system is performing an infinite path, which could be improved with tuning at gains of the positioning scheme, but for this aircraft development, are considered acceptable.

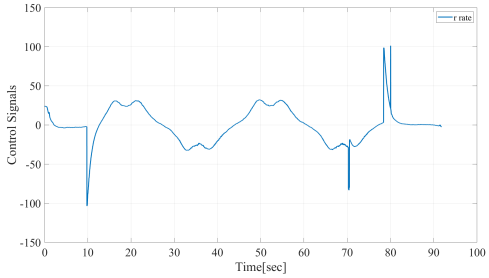
-Control signals



(a) p rate control signal.

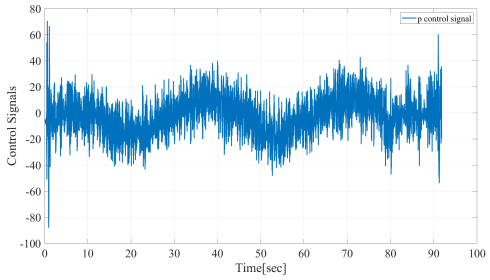


(b) q rate control signal.

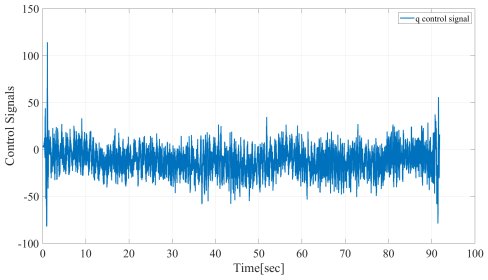


(c) r rate control signal.

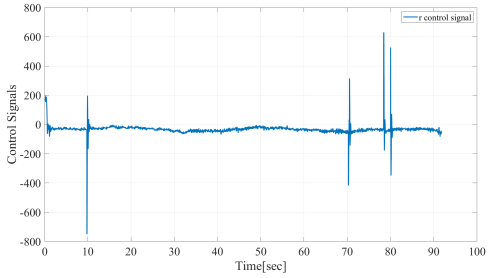
Figure 7.23: Desired angular velocity p, q, r of Quadrotor Experiment 1.



(a) p control signal.



(b) q control signal.

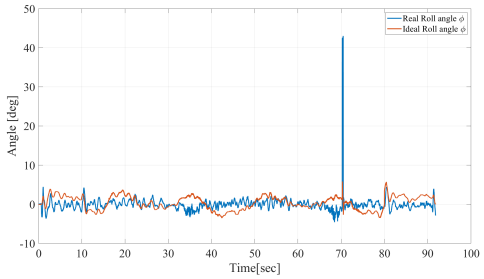


(c) r control signal.

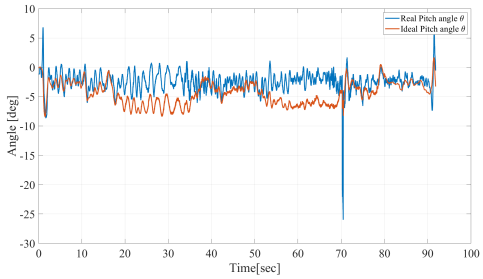
Figure 7.24: Angular velocities Quadrotor Experiment 1.

This part of the analysis is the important field of this experiment, where the combination of a path to perform an infinite is directly related to inputs, and internally as a combination of signals that perform this motion, if the system is not correctly developed it would tend to perform as a noncontinuous system, for this case is not present that behavior, it developed an acceptable result, ideal to demonstrate that this system could perform many of experiments.

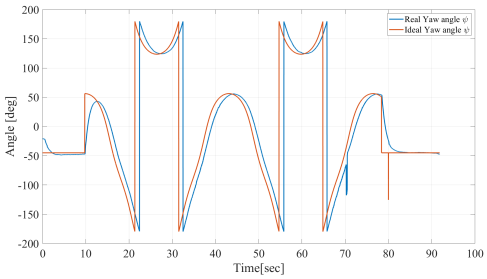
-Attitude



(a) Roll angle.



(b) Pitch angle.



(c) Yaw angle.

Figure 7.25: Attitude angles of Quadrotor Experiment 1.

From angle analysis, this system tends to perform motion with a zero deg cross even if the system asks for slight changes in angles, but when is exited with a correct signal that this system recognizes it develops the shape and angle, also spikes are presented, but those are mitigated by the system. A demonstration of the affirmation mentioned before is shown in Figure 7.25c, which performs an ideal behavior, due to an input that is correctly introduced that reason is important to characterize the system for a limitation analysis as well as the design of trajectories; is important to mention that those limitations could be improved, but for this results are presented

as limitations.

7.1.2.2 Experiment 2: 0.05rev/s

-Trajectory

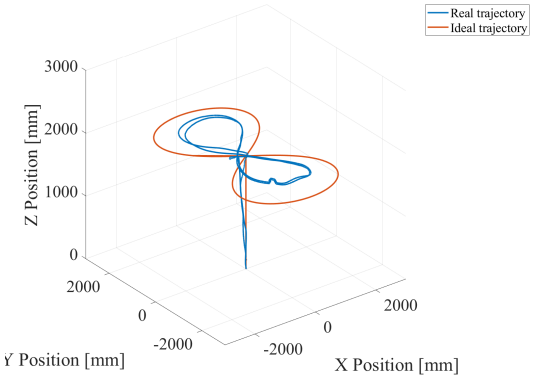


Figure 7.26: XYZ trajectory tracking, real vs ideal.

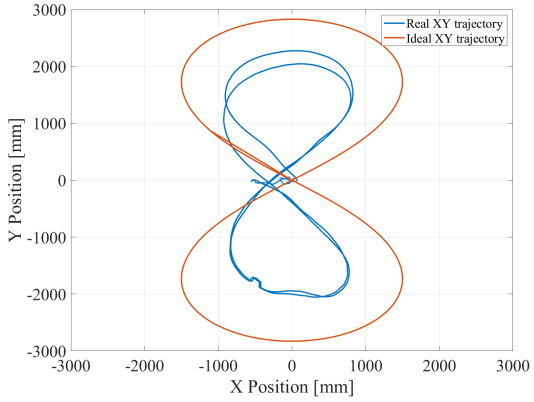
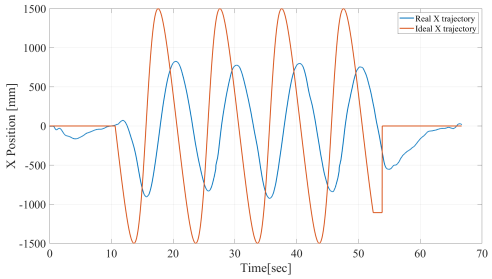
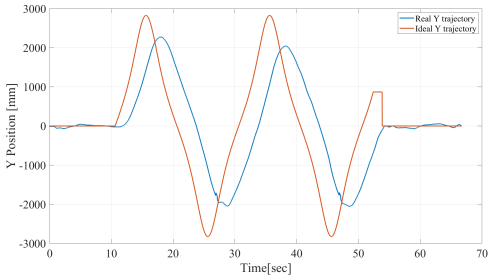


Figure 7.27: XY trajectory tracking, real vs ideal.

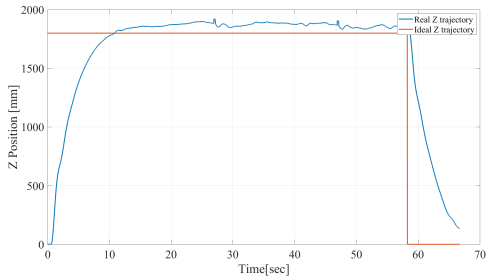
This second development of the infinite path develops a system tracking error wider than the previously presented, due to the response of the system, which is reflected as a reduction of the magnitudes developed, which would be presented below, but also at the geometrical representation of the previous graph shows a outdistance form the geometry, following the geometry but not as expected.



(a) X trajectory tracking, real vs ideal.



(b) Y trajectory tracking, real vs ideal.

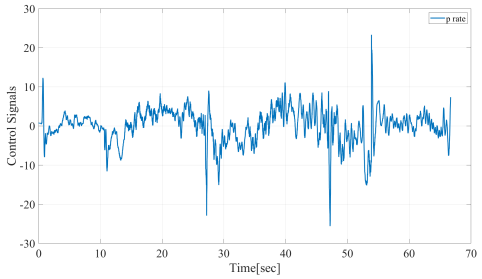


(c) Z trajectory tracking, real vs ideal.

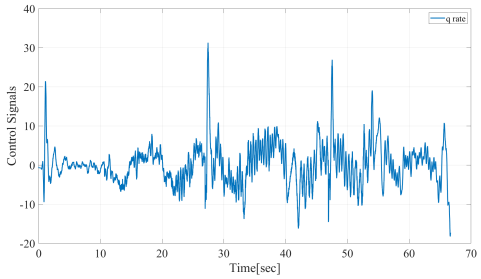
Figure 7.28: X-Y-Z vs Time trajectory tracking.

Those signals reported show the behavior previously mentioned, if the response could improve it would follow them, but in this case is limited to this behavior, which in one sense follows the trajectory, but not with the magnitudes expected.

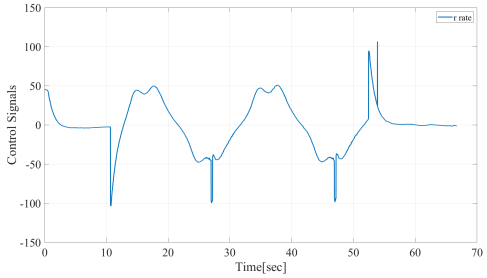
-Control signals



(a) p rate control signal.

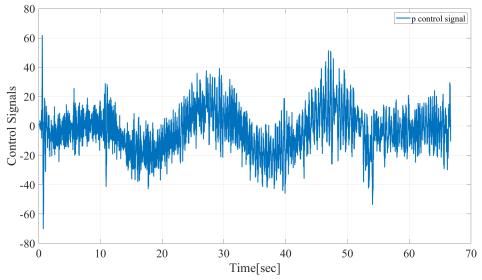


(b) q rate control signal.

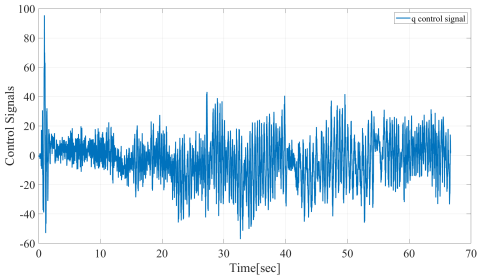


(c) r rate control signal.

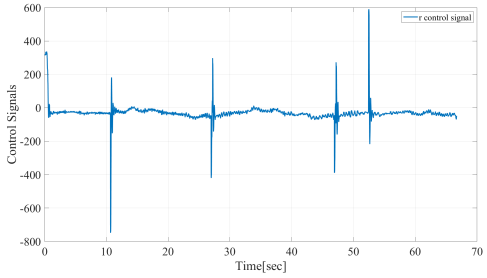
Figure 7.29: Desired angular velocity p, q, r of Quadrotor Experiment 2.



(a) p control signal.



(b) q control signal.

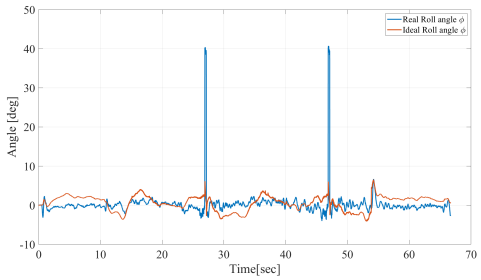


(c) r control signal.

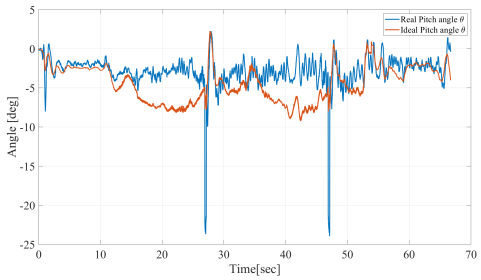
Figure 7.30: Angular velocities Quadrotor Experiment 2.

Control directly reflects a similar behavior as the first infinite experiment, due to a similar input having a system that feeds it with those signals to perform a certain motion, limited by the boundaries established, but stable for critical missions.

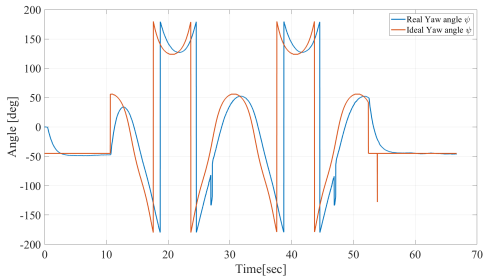
-Attitude



(a) Roll angle.



(b) Pitch angle.



(c) Yaw angle.

Figure 7.31: Attitude angles of Quadrotor Experiment 2.

Previous results shows a pertinence of the angles desired from the system, limited by its position feedback and its accomplish, in terms so signal, results are acceptable. Perturbations on the systems are induced due to environmental conditions, as well as aerodynamics effects which in these motions would be reflected.

7.1.3 Helical Path

A helical5 experiment is developed to test the system in a full combination of inputs, where is necessary not to just have tracking on an XY plane, also a variable thrust input is required, some systems could not perform this kind of mission due to max

control authority or due to stable operations, at this case is demonstrate a non-dependent system on conditions.

-Trajectory

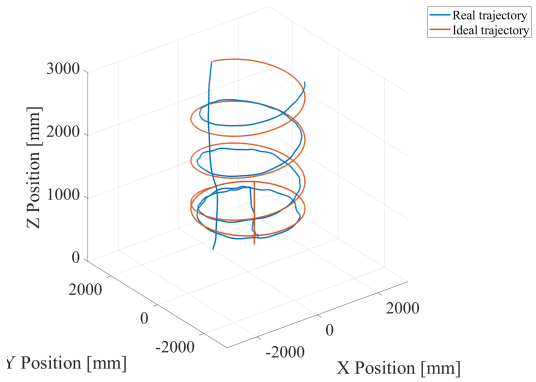


Figure 7.32: XYZ trajectory tracking, real vs ideal.

The trajectory visualize in the 3D space shows a correct tracking of the trajectory, with a small offset due to delay but it shows a complete development even though is a change in height, which also allow us to virtually conclude that this system mitigates the ground effect showing a similar behavior on the whole experiment.

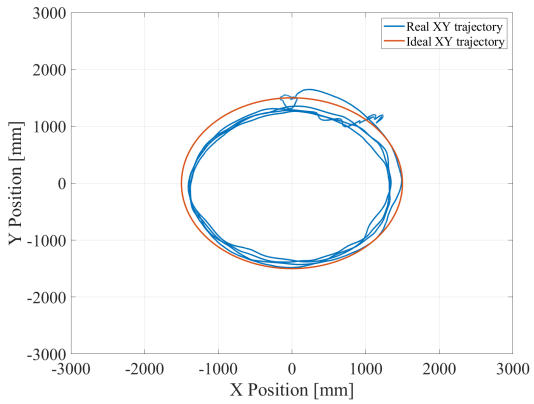
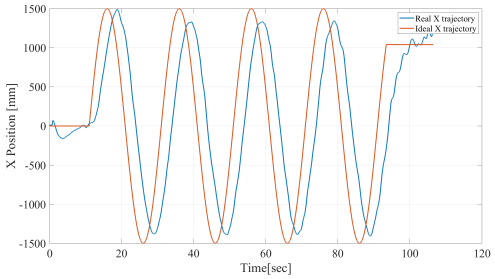
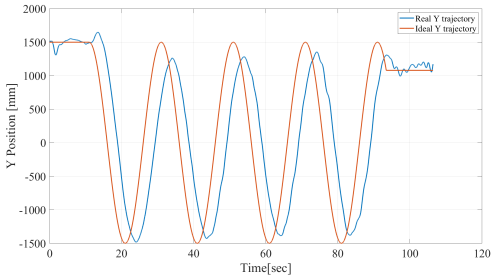


Figure 7.33: XY trajectory tracking, real vs ideal.

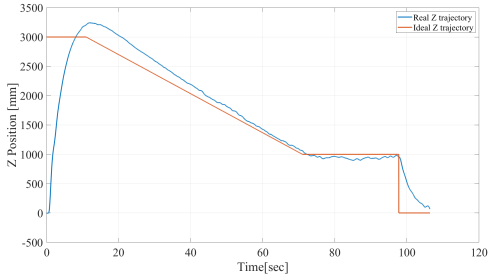
On the 2D transient response is seen it that this system still with a small error, having a maximum of 300mm, less than the aircraft length.



(a) X trajectory tracking, real vs ideal.



(b) Y trajectory tracking, real vs ideal.

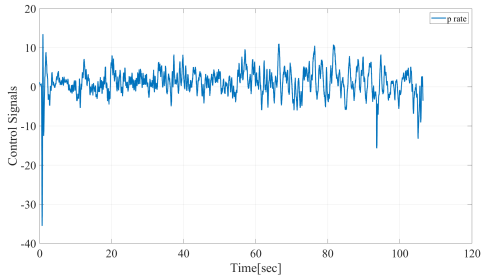


(c) Z trajectory tracking, real vs ideal.

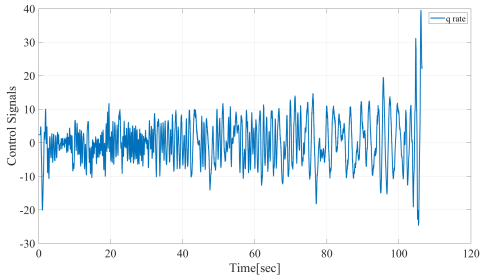
Figure 7.34: X-Y-Z vs Time trajectory tracking.

With the separate tracking trajectory is demonstrated that those X-Y-Z visualize at other graphs show real data and no perspective dependent, even though the magnitude is partially the same as the desired, which is only out of phase, due to delay, but in terms of trajectory development, it results are impressively accurate.

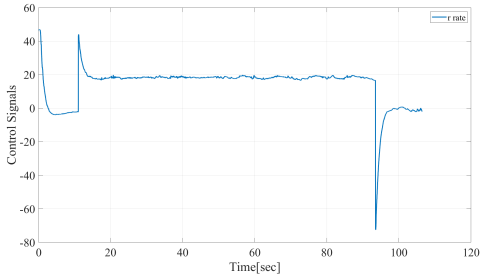
-Control signals



(a) p rate control signal.

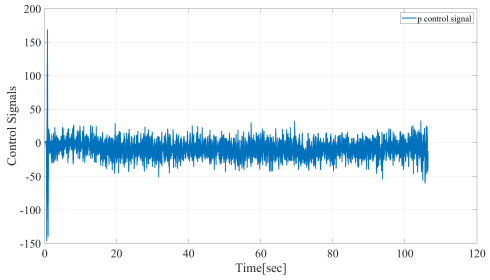


(b) q rate control signal.

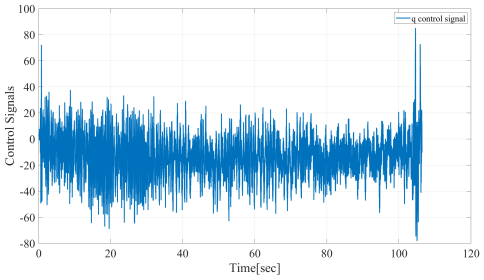


(c) r rate control signal.

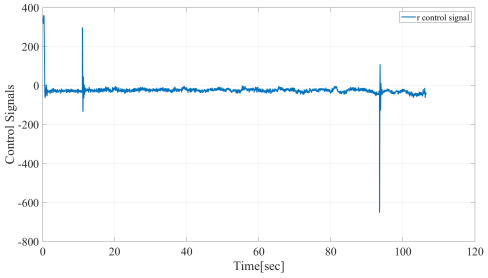
Figure 7.35: Desired angular velocity p, q, r of Quadrotor Spiral Experiment 1.



(a) p control signal.



(b) q control signal.

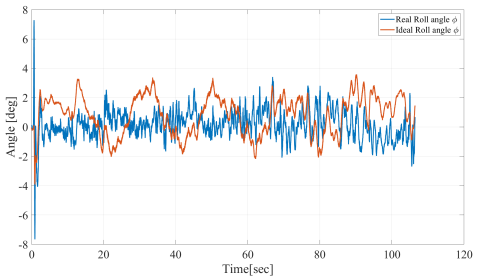


(c) r control signal.

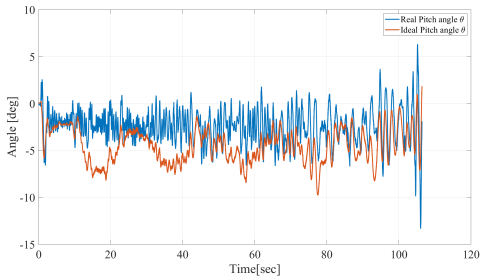
Figure 7.36: Angular velocities Quadrotor Helical Experiment 1.

On the other hand, control shows expected results, due to the development of a trajectory that follows an axis, and it performs tangent to them it is a sine required for this development, which is partially the same as the signal presented, it is just an induce noise on them.

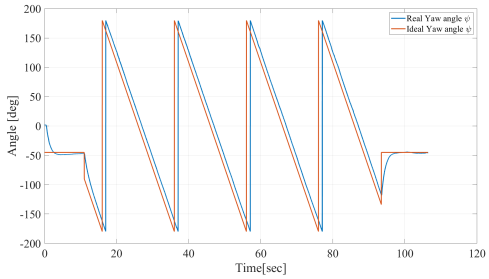
-Attitude



(a) Roll angle.



(b) Pitch angle.



(c) Yaw angle.

Figure 7.37: Attitude angles of Quadrotor Helical Experiment 1.

For this case, the angular analysis shows an interesting result, which is physically damped, but even though the system develops a mapping action with less magnitude, concluding that is not necessary for the development of the trajectory.

7.1.4 Hover

This test allows us to characterize the drift of the system, including take-off and landing, where it performs a zero desired position on XY plane and fixed height.

-Trajectory

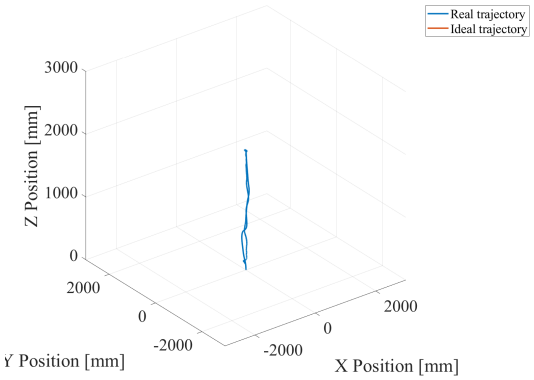


Figure 7.38: XYZ trajectory tracking, real vs ideal.

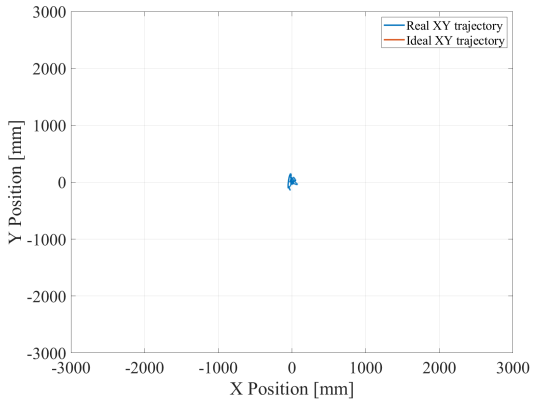
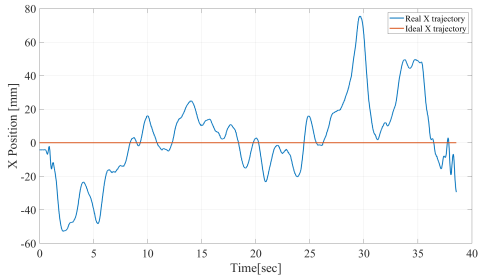
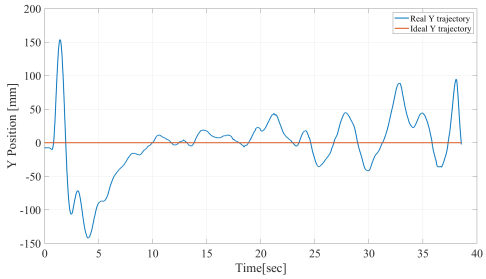


Figure 7.39: XY trajectory tracking, real vs ideal.

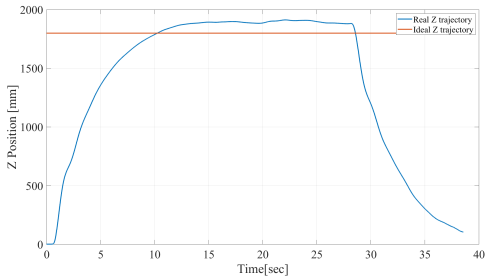
For this case XYZ and XY analysis do not reflect concluding data, due to perspective, it only visualizes the system behavior on the take-off and landing process, which shows a correct development of those orders.



(a) X trajectory tracking, real vs ideal.



(b) Y trajectory tracking, real vs ideal.

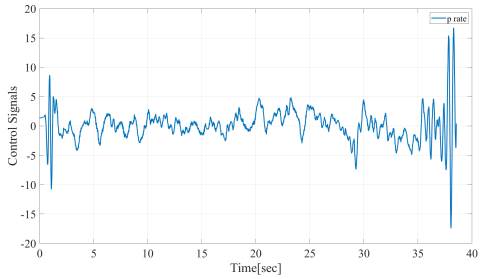


(c) Z trajectory tracking, real vs ideal.

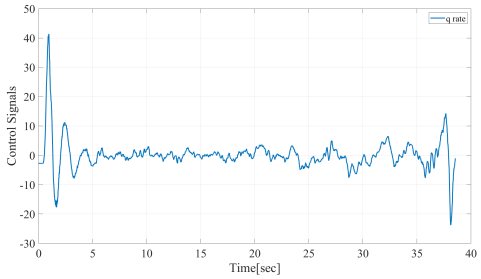
Figure 7.40: X-Y-Z vs Time trajectory tracking.

Individual graphs are shown the position errors of the system, in this case, maximum magnitudes of them are performed during the take-off and landing process, and at stable operation are bound to 50mm of an error on every axis.

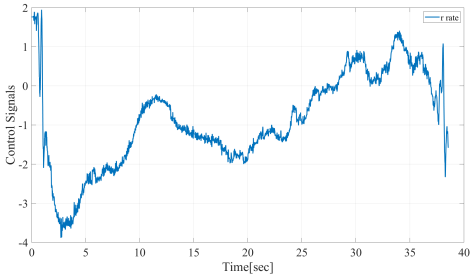
-Control signals



(a) p rate control signal.

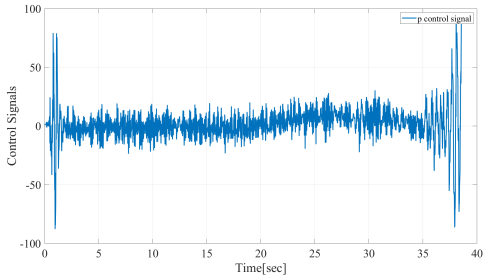


(b) q rate control signal.

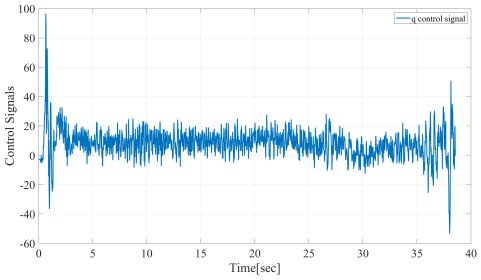


(c) r rate control signal.

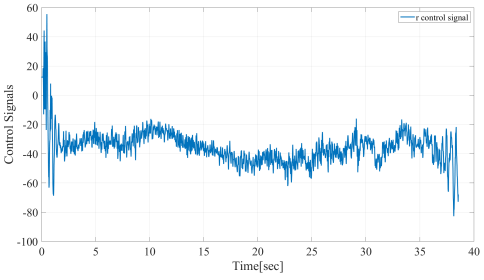
Figure 7.41: Desired angular velocity p, q, r of Quadrotor Hover Experiment 1.



(a) p control signal.



(b) q control signal.

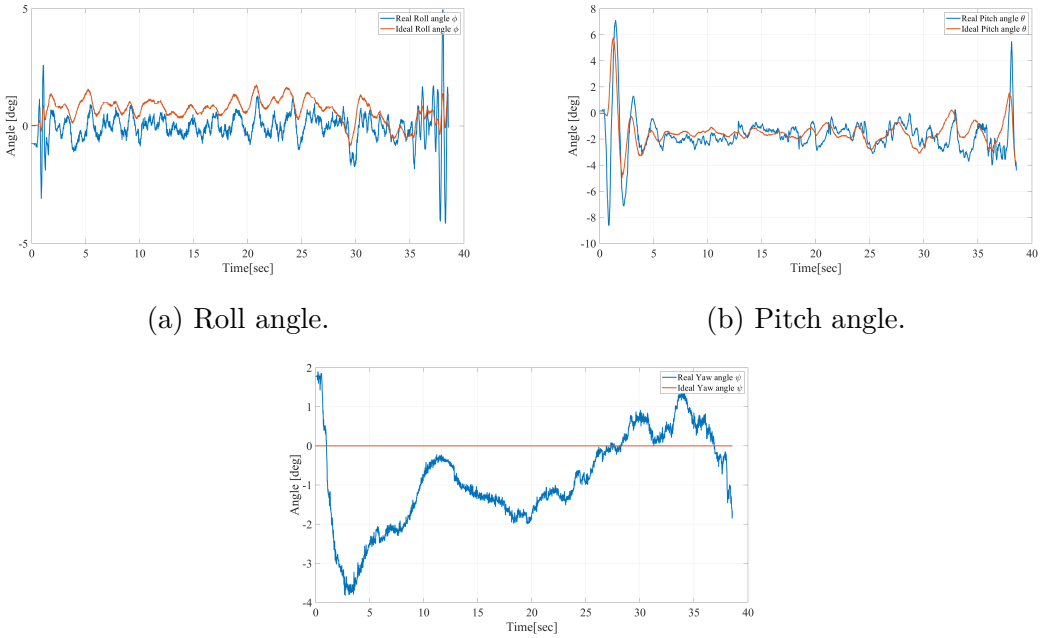


(c) r control signal.

Figure 7.42: Angular velocities Quadrotor Experiment 1.

Those results, allow us to visualize important data that is for conclusion on previous experiments, where this is the noise-induced to the system due to natural system stabilization, becoming into small references required to mitigate manufacture errors and aerodynamics effects, on both cases, are developed small signals that in comparative with inputs signals accomplish are low signals.

-Attitude



(a) Roll angle.

(b) Pitch angle.

(c) Yaw angle.

Figure 7.43: Attitude angles of Quadrotor Hover Experiment 1.

An angular analysis is ideal for small angle determination, where this system correctly develops half of the angles required for environmental mitigation, using that is possible to conclude that the orientation control algorithm is correctly developed, the section that should be improved is related to position one.

7.2 Convertible Tricopter

Experiments and validation perform on this prototype allow us to the characterization of the system as well recognizance of some unexpected behaviors, by that reason, it were selected some paths to accomplish and some inputs ramps; is important to mention that they were bounded to a closed space due to tracking purpose, where the cameras of the laboratory are required for data tracking.

7.2.1 Circle

For the circular trajectory accomplish, it have selected a circle of 1750 mm of radius, 1800 mm of height, and 0.03 rev/s of velocity, for this case, it is assessing the tilting mechanism which allows us to have that kind of movement without using an input on the rotors, those are only controlled by the mixer for stabilization purpose.

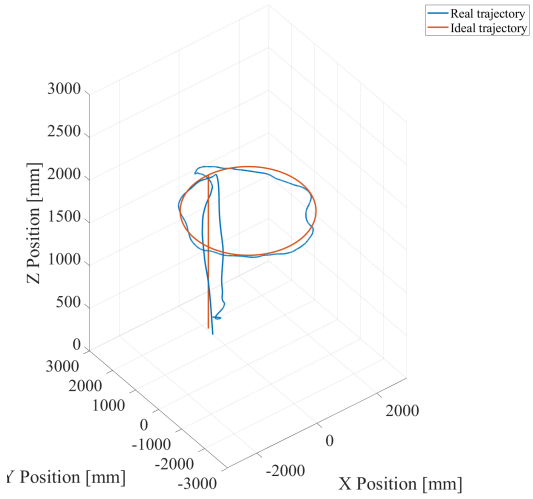


Figure 7.44: XYZ trajectory tracking, real vs ideal.

Geometrical errors are expected due to less resolution on actuators, which in this sense is visualized by a circle made of trajectories based online, in terms of

pertinence to the trajectory it is still at correct values, having drift but with an acceptable tracking error.

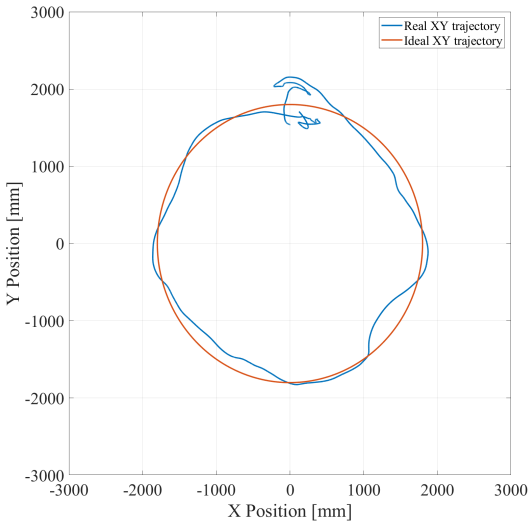
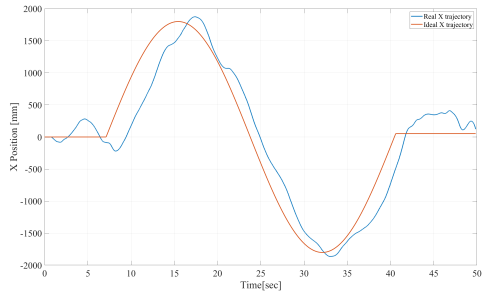
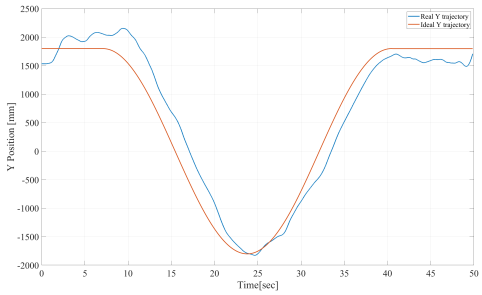


Figure 7.45: XY trajectory tracking, real vs ideal.

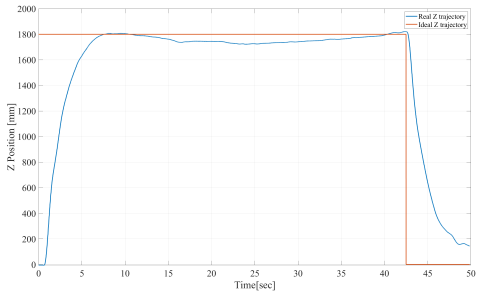
At this XY visualization are shown areas that are affirmations of that segmentation mentioned before.



(a) X trajectory tracking, real vs ideal.



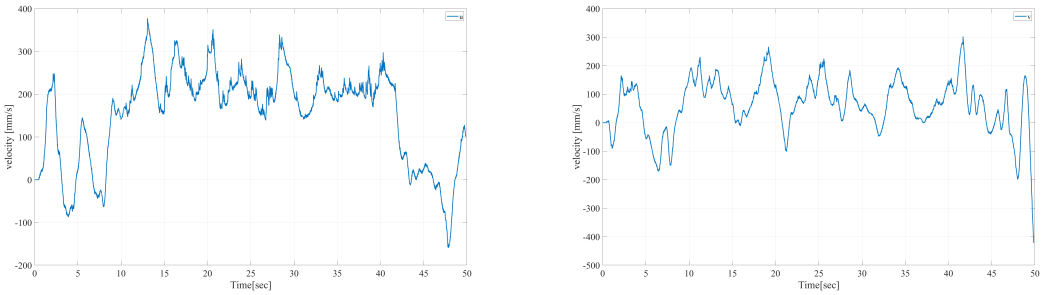
(b) Y trajectory tracking, real vs ideal.



(c) Z trajectory tracking, real vs ideal.

Figure 7.46: X-Y-Z vs Time trajectory tracking.

Individual visualization allows us to conclude that this system is performing the trajectory desired, some areas are not completely mapped with the desired signals due to limitations on actuators, but others are fast responsive which means less delay in comparison with the other system, especially for those physical effects due to inertial and damping related to the aircraft design which allows us to have some fast response on some specifics points that in the other would create instability.



(a) u Velocity.

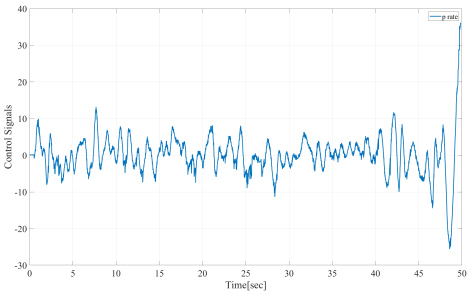
(b) v Velocity.

Figure 7.47: u, v velocities.

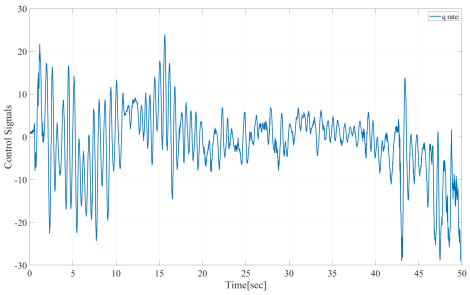
For this system is also important to analyze the u and v velocity, that due to fixed-wing effects, which induce lift force when the system is traveling at high values. In this case, it is induced 0.4m/s as maximum magnitude for u, negligible for analysis case.

-Control signals

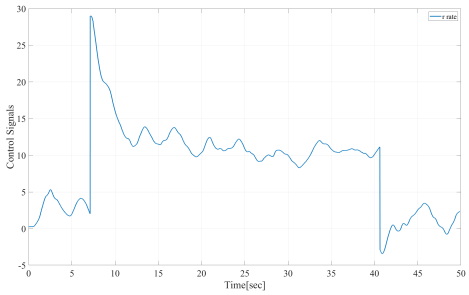
As the first experiment of this prototype, is important to mention that those systems share a propulsion system but with different structures, giving a result that this system has more inertia, which would be related to magnitudes required for maneuvers as well as less oscillation due to physical damping.



(a) p rate control signal.



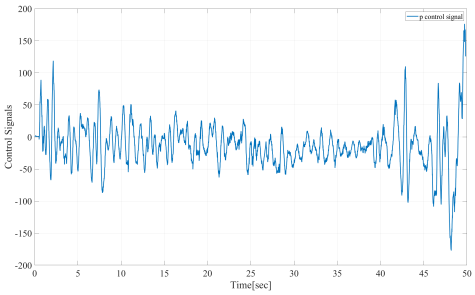
(b) q rate control signal.



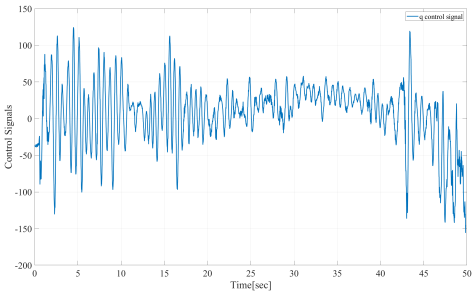
(c) r rate control signal.

Figure 7.48: Desired angular velocity p, q, r of Convertible Tricopter Circle Experiment.

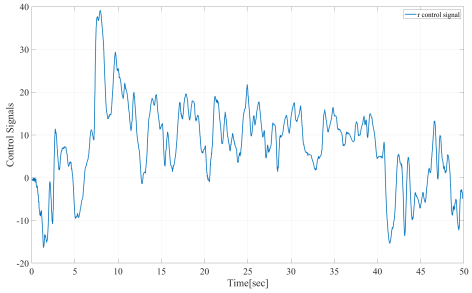
A comparison between Figures 7.5 and 7.48 shows the difference in magnitude and frequency, the same experiment but with different approach, for stable operation is considered the second one as better, which allows stabilization with less oscillation.



(a) p control signal.



(b) q control signal.



(c) r control signal.

Figure 7.49: Angular velocities of Convertible Tricopter Circle Experiment.

Another effect of less frequency of signals is reflected in the final signal, which is clear to visualize, for actuators this is a better signal due to noise reduction which reflect into a stable output.

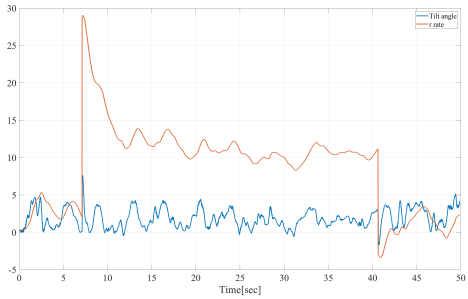


Figure 7.50: Tilt angle (δ) vs r rate control signal Circle Experiment.

This graph allows us to visualize the relation between r and the tilting angle, which has a direct relational, using them to perform that rotation, is important to

mention that this angle is not just fed by that, it is also used for linear movement, pitch reactions, and other effects.

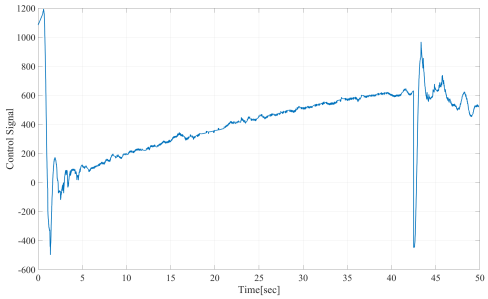
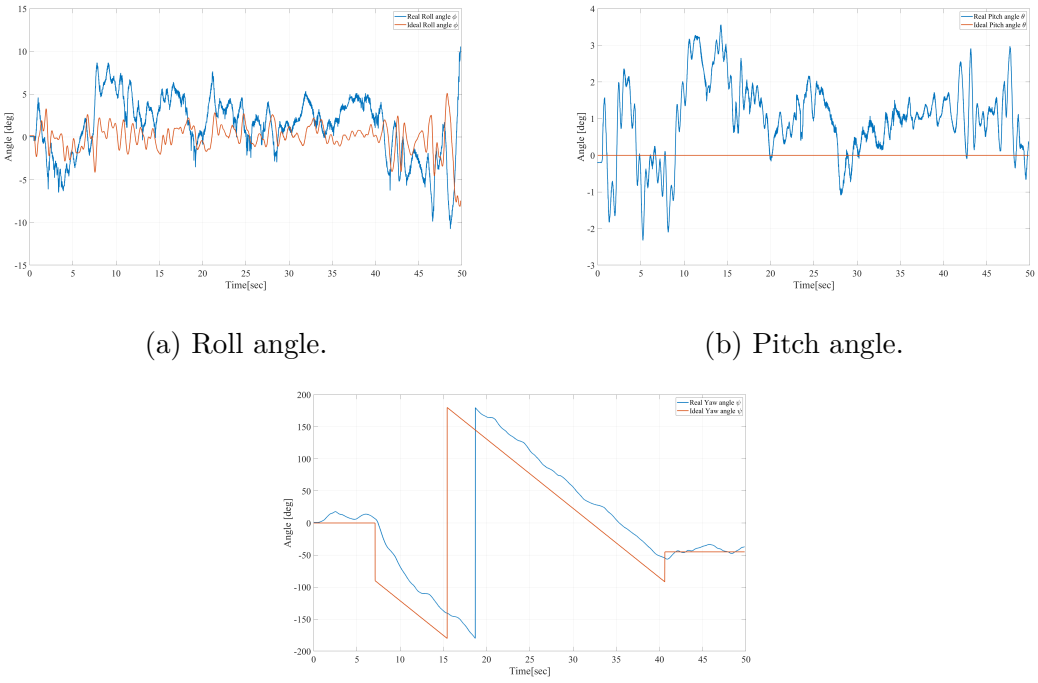


Figure 7.51: Thrust Control Signal.

Another element to analyze in this configuration is related to thrust, which is a parameter to analyze two parameters, first is related to the integral term which mitigates the battery drain, and the other element due to aerodynamics when it induces enough velocity to the main wing which start producing lift directly reflecting a reduction on thrust component for flight.

-Attitude



(a) Roll angle.

(b) Pitch angle.

(c) Yaw angle.

Figure 7.52: Attitude angles of convertible tricopter circle experiment.

For angle stabilization is important to mention that the mixing matrix for this aircraft considers a non-equal distribution of rotors for body axes, also the inclusion of newer actuator to a configuration of multi-rotors increases the complexity of this system which is reflected in the signals previously presented, that shows more divergence on certain signal, especially at roll angle, which is stabilized by just two actuators (rotors for this case) and it should mitigate the aerodynamics effects due to wing inclusion, in some cases damping effects are presented but its mass also increases inertial, which is required to compensate with that configuration of two rotors, in terms of performance, is the most difficult axes to have it in control a bounded to same magnitudes than the others.

7.2.2 Ellipse

This experiment allows us to separate the areas of forwarding flight with little influence on rotation and circular rotation, reflecting an analyze of the system in both circumstances.

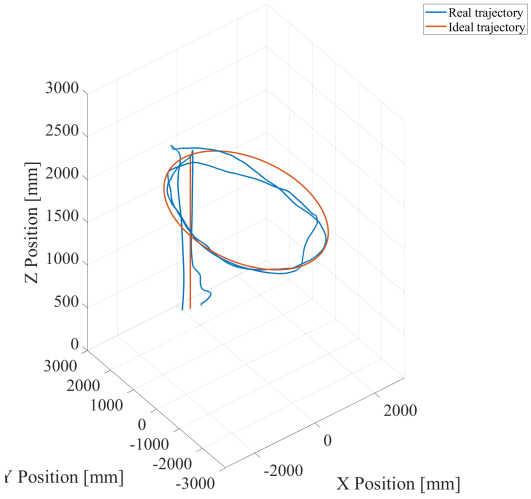


Figure 7.53: XYZ trajectory tracking, real vs ideal.

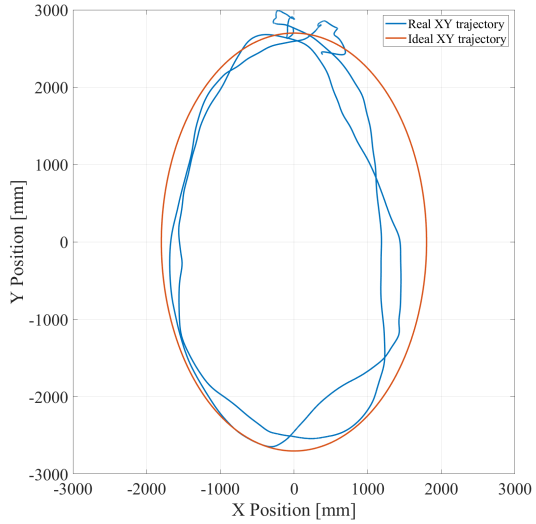
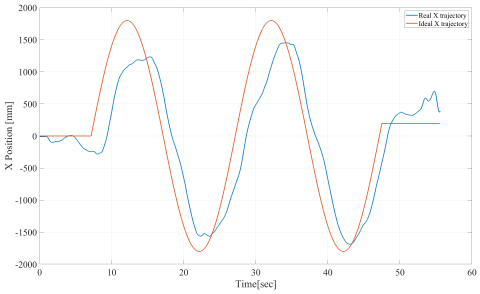
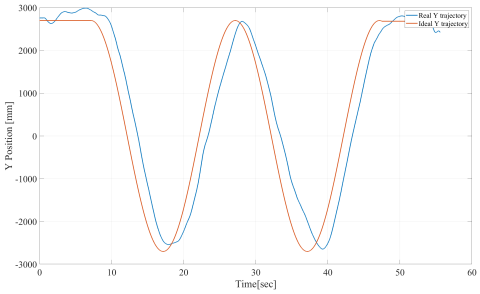


Figure 7.54: XY trajectory tracking, real vs ideal.

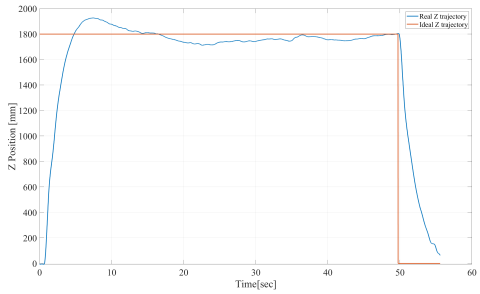
The trajectory from this system has a direct relation with actuators, which in the rotation tends to unperformed but at straight movements it has advantages. (Is important to mention that the unperformed effect mentioned is related to less quality tracking but in terms of small UAVs its performance is acceptable).
At the maximum point of divergence, it shows a 500mm, which considering the arm length of 450mm, stills on parameters; this point of high error was also induced by a divergence on track, which is performed by a delay on the system, been mitigate it on a couple of seconds that stabilize the system and performs a tracking with 100mm of average error, and areas of less than that.



(a) X trajectory tracking, real vs ideal.



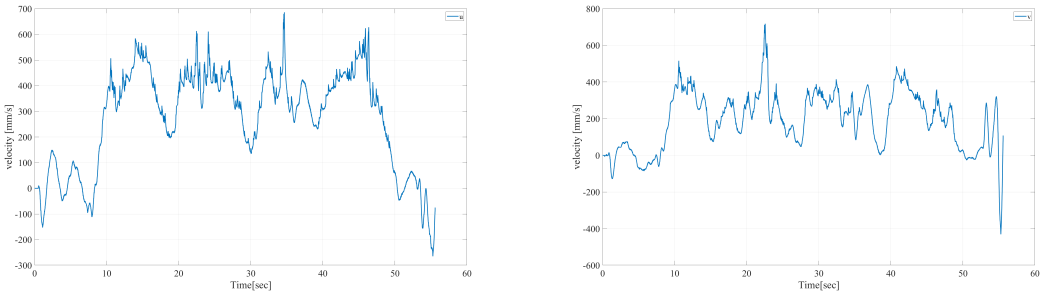
(b) Y trajectory tracking, real vs ideal.



(c) Z trajectory tracking, real vs ideal.

Figure 7.55: X-Y-Z vs Time trajectory tracking.

Those separate signals allow us to have the affirmation that straight flight has better tracking and performance, directly observed in Figure 7.55b, and in close rotations performance decrease having a magnitude reduction.



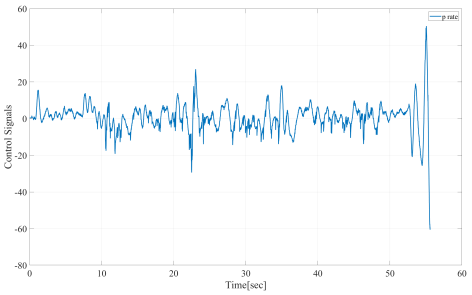
(a) u Velocity. (b) v Velocity.

Figure 7.56: u, v velocities.

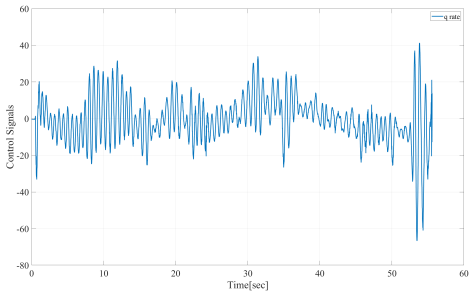
Important data from those graphs are related to the areas where is presented maximum u velocity, which on control signals would be used to visualize the relation of this velocity with the adhesion of force to the system (lift).

-Control Signals

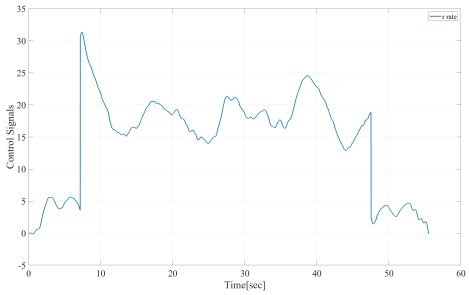
At data shown below would consider the signals required by the system to perform the path, but in this case, the velocity desired would show an influence of the drag and tilting mechanism on the system that should perform a pitch-less condition.



(a) p rate control signal.

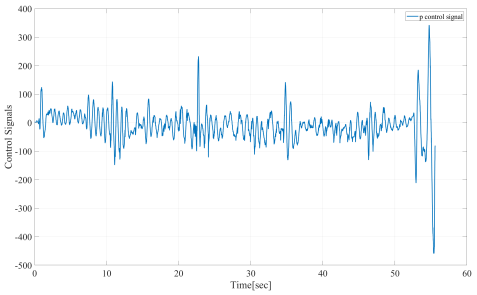


(b) q rate control signal.

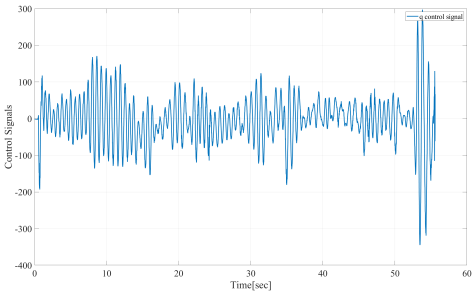


(c) r rate control signal.

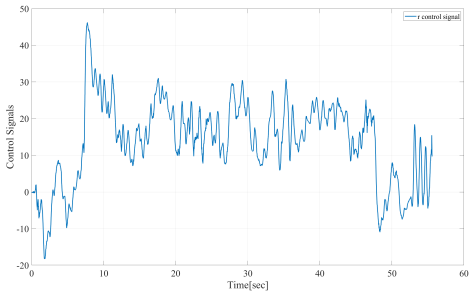
Figure 7.57: Desired angular velocity p, q, r of Convertible Tricopter Ellipse Experiment.



(a) p control signal.



(b) q control signal.



(c) r control signal.

Figure 7.58: Angular velocities convertible tricopter ellipse experiment.

A direct relation between this tracking and specific areas is shown in that signals, an essential element to mention is that this system is intended for planar movements for that reason the system seeks zero conditions.

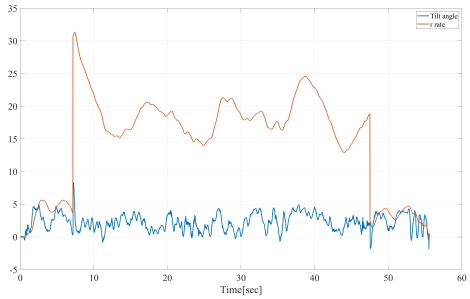


Figure 7.59: Tilt angle (δ) vs r rate control signal Ellipse Experiment.

For this case the relation is only shown as a motion change point and offset for those other points that are required, the other magnitude is due to the position

input.

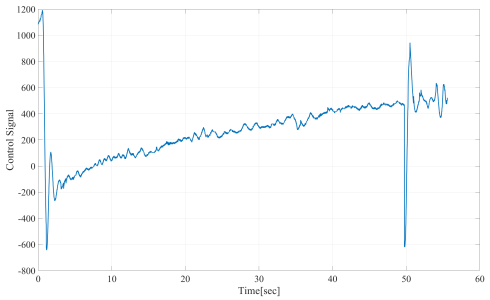
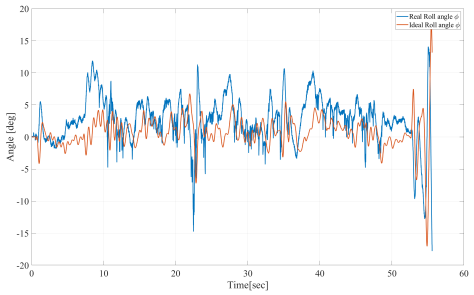


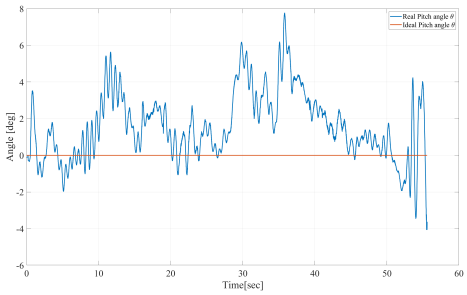
Figure 7.60: Thrust Control Signal.

It should be considered the slope of the previous graph, which should be like Figure 7.51, but its magnitude is less than that for this experiment due to an increase of the force developed by the wing, which is according to the u velocity previous highlighter.

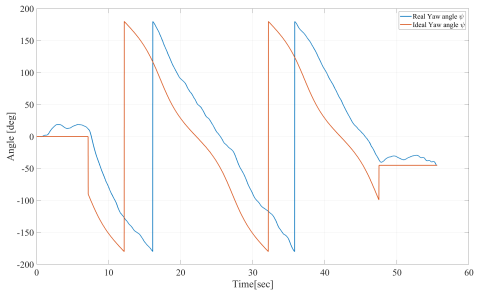
-Attitude



(a) Roll angle.



(b) Pitch angle.



(c) Yaw angle.

Figure 7.61: Attitude angles of convertible tricopter ellipse experiment.

For this path where is required more aggressive control inputs it performs better, but at pitch angle tends to lack performance due to the dynamics coupling, especially at the points of circular rotation; for the yaw angle, it has identical performance to the ideal.

7.2.3 Infinite

For a convertible aircraft that has advanced actuators implementations, some missions would perform better, at this case a continuous drift induced by p and r would be absorbed by the tilting mechanism, in that sense, this experiment is developed to taste that performance, using 1500mm as the radius of circles, 0.05rev/s of velocity and 1800mm as height, same as the second test on quadrotor configuration.

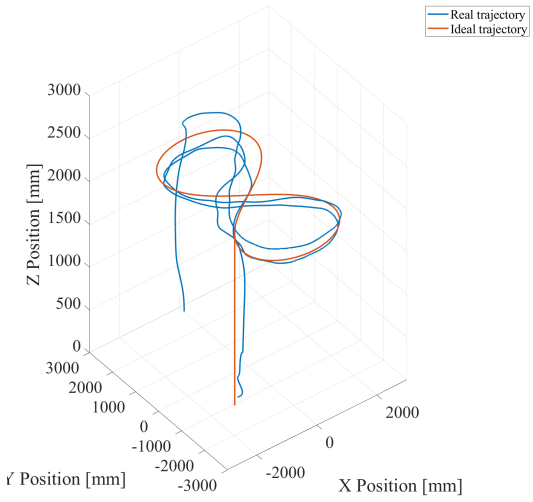


Figure 7.62: XYZ trajectory tracking, real vs ideal.

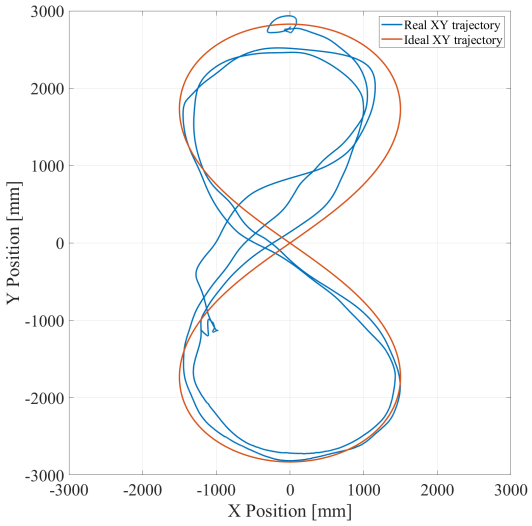
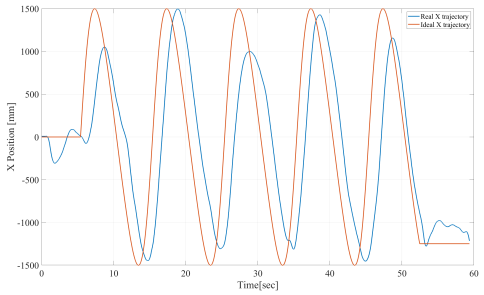
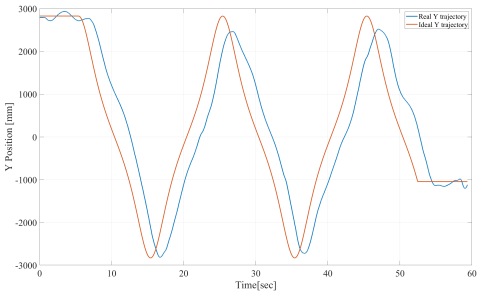


Figure 7.63: XY trajectory tracking, real vs ideal.

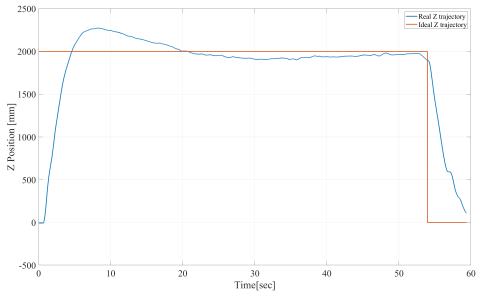
Using trajectory tracking it could be considered that the performance of this aircraft is better than in the son of multi-rotors due to a combination of actuators that could perform that mission without coupling other movements, just the intended are performed, for this case, the maximum error is 300mm even less than the length of the aircraft, which means is better than expected, especially by its dimensions and limitations due to the implementation of the complex structure.



(a) X trajectory tracking, real vs ideal.



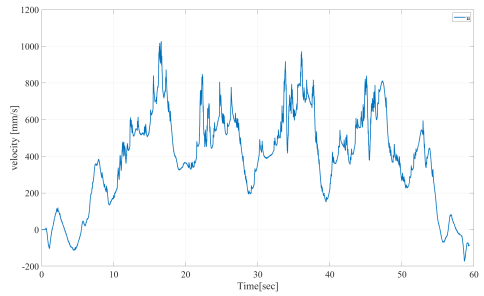
(b) Y trajectory tracking, real vs ideal.



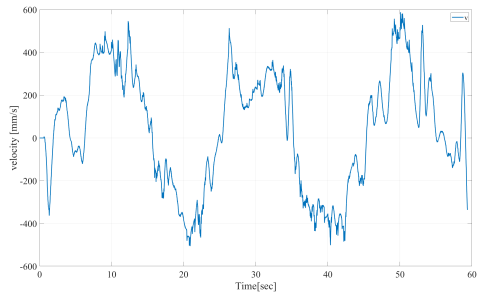
(c) Z trajectory tracking, real vs ideal.

Figure 7.64: X-Y-Z vs Time trajectory tracking.

At this scope is shown that the system performance is maintained even if the trajectory is repeated, a perturbation is also presented at the third oscillation, but neglected and recovered.



(a) u Velocity.



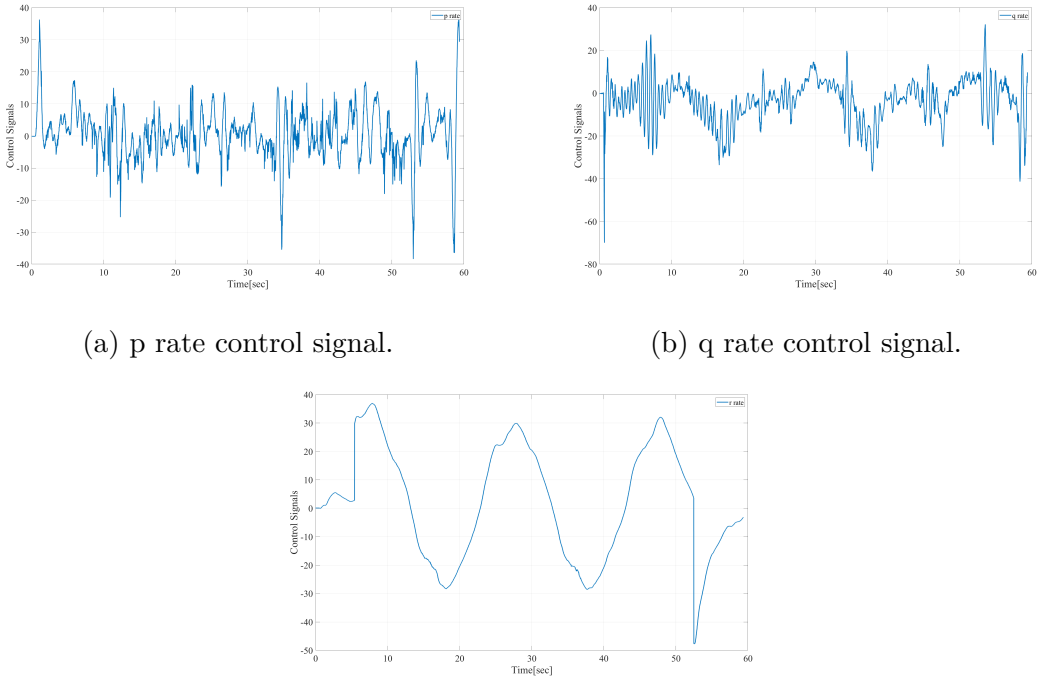
(b) v Velocity.

Figure 7.65: u, v velocities.

For this case, the specifics point at it was performing u of 1m/s,c which are

small spikes that would be seen in the system as small decreases in thrust adhesion on the graphs below.

-Control signals

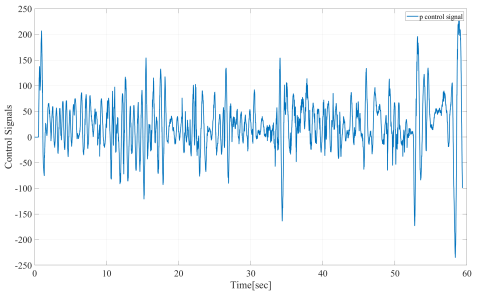


(a) p rate control signal.

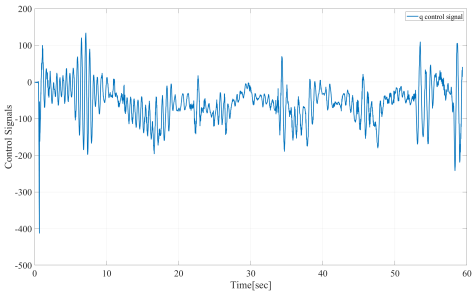
(b) q rate control signal.

(c) r rate control signal.

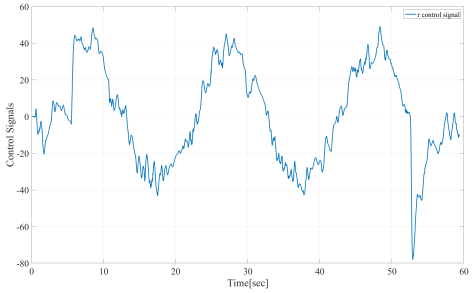
Figure 7.66: Desired angular velocity p, q, r of Convertible Tricopter Ellipse Experiment.



(a) p control signal velocity.



(b) q control signal velocity.



(c) r control signal.

Figure 7.67: Angular velocities convertible tricopter infinite experiment.

These control signals reflect the system response to the trajectory demands, which perform a coupling of sine signal due to the natural behavior of that trajectory, by that reason both control layers show that response, to perform the trajectory but also to as planar as possible flight.

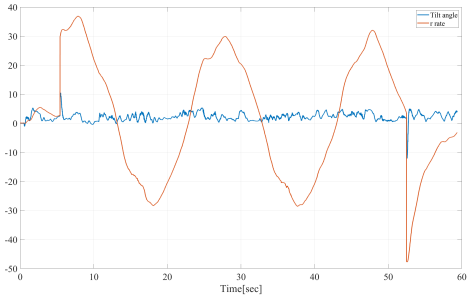


Figure 7.68: Tilt angle (δ) vs r rate control signal Infinite Experiment.

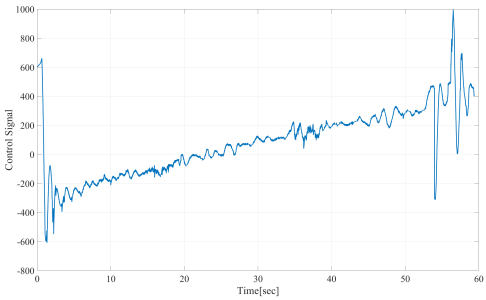
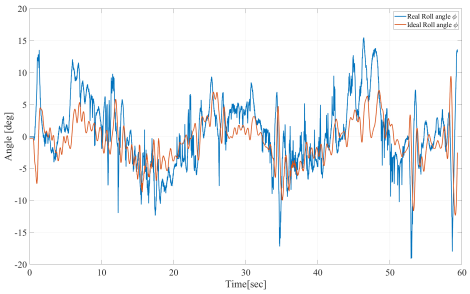


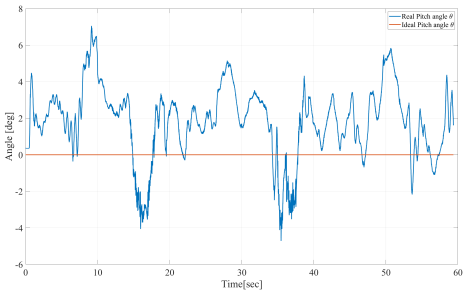
Figure 7.69: Thrust control signal.

This figure already visualizes the effects mentioned before, those spikes of 1m/s are appreciated as small valleys, in the case of holding data, it could perform a lift force presence on the system, with results expected in experiments below.

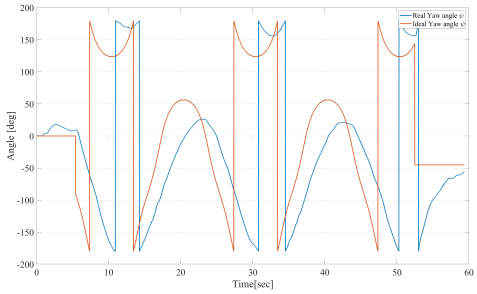
-Attitude



(a) Roll angle.



(b) Pitch angle.



(c) Yaw angle.

Figure 7.70: Attitude angles of convertible tricopter infinite experiment.

Angles in this experiment results in desired signals for roll (Figure 7.70a), the

system map the desired signal and performs it, in some cases, it has some overshoot due to actuation and trajectory coupling but is fast recovered by the system, on the other hand, there is the pitch angle, which should be 0 for pitch-less requirement, but in this case, the system is not as robust as intended, due to its aerodynamic behavior, at cruise flight, it would be a force to implement that angle, that reason is not to implement a more aggressive control signal, at this hover / low-speed trajectories is not necessary to accomplish the missions.

7.2.4 Hover

A hover test is a specific experiment to visualize the quality of the system on the small movements and manufacture deviations that induce drift, also on a convertible aircraft has the objective to evaluate its performance of multi-rotor scope with or without the extra actuators, for this case, it is used the tilting mechanism for the *yaw* rotation.

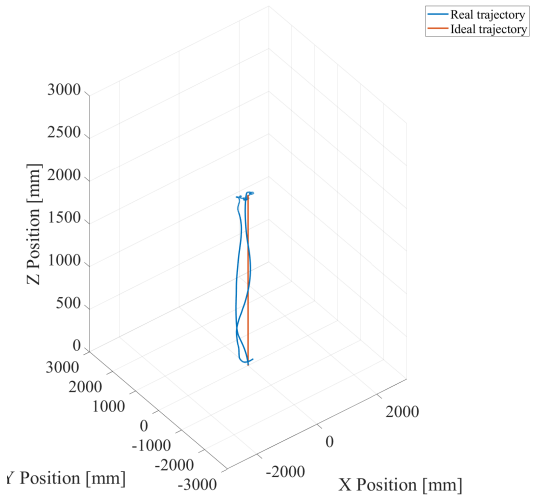


Figure 7.71: XYZ trajectory tracking, real vs ideal.

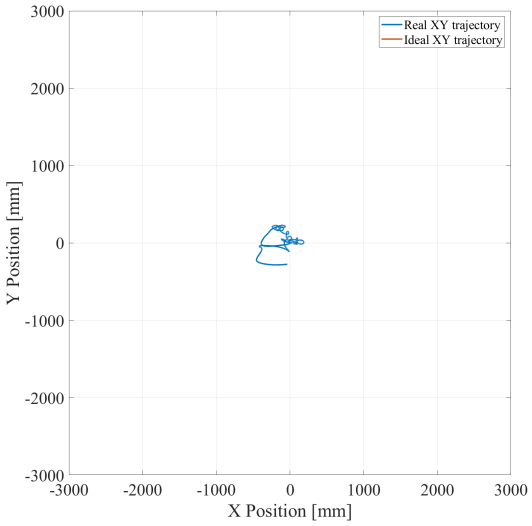
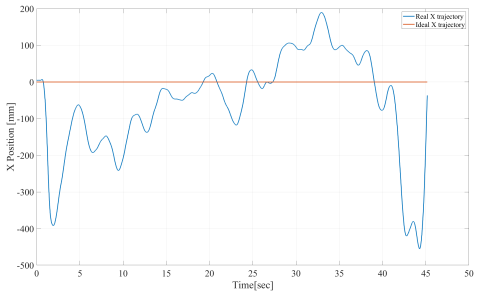
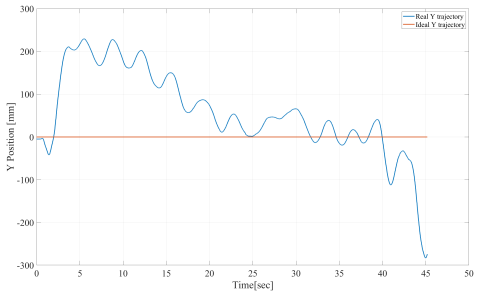


Figure 7.72: XY trajectory tracking, real vs ideal.

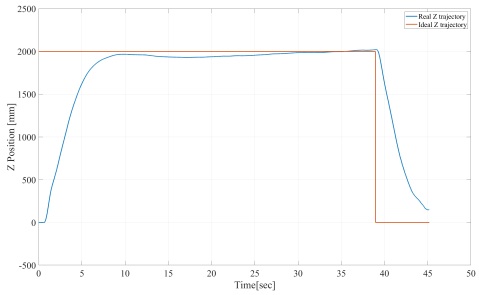
Taking into account the dimension of the aircraft, it is a drift equivalent to it, most of them are related to yaw, which in small movements is not damped by the system and actuators could not perform those small corrections, giving results of movement on space, which correspond to a maximum of 200mm, consider also take-off and landing process.



(a) X trajectory tracking, real vs ideal.

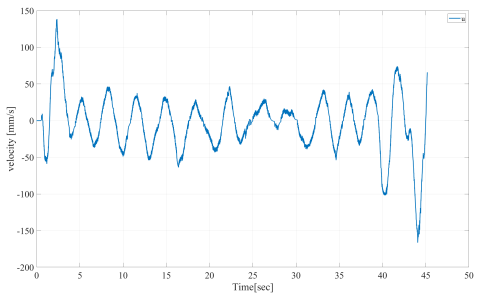


(b) Y trajectory tracking, real vs ideal.

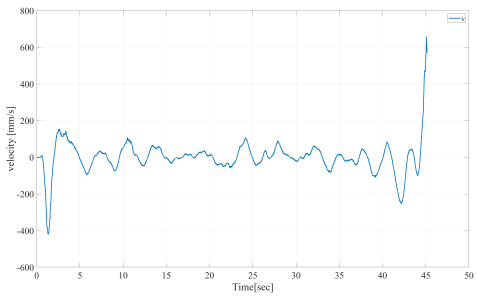


(c) Z trajectory tracking, real vs ideal.

Figure 7.73: X-Y-Z vs Time trajectory tracking.



(a) u Velocity.

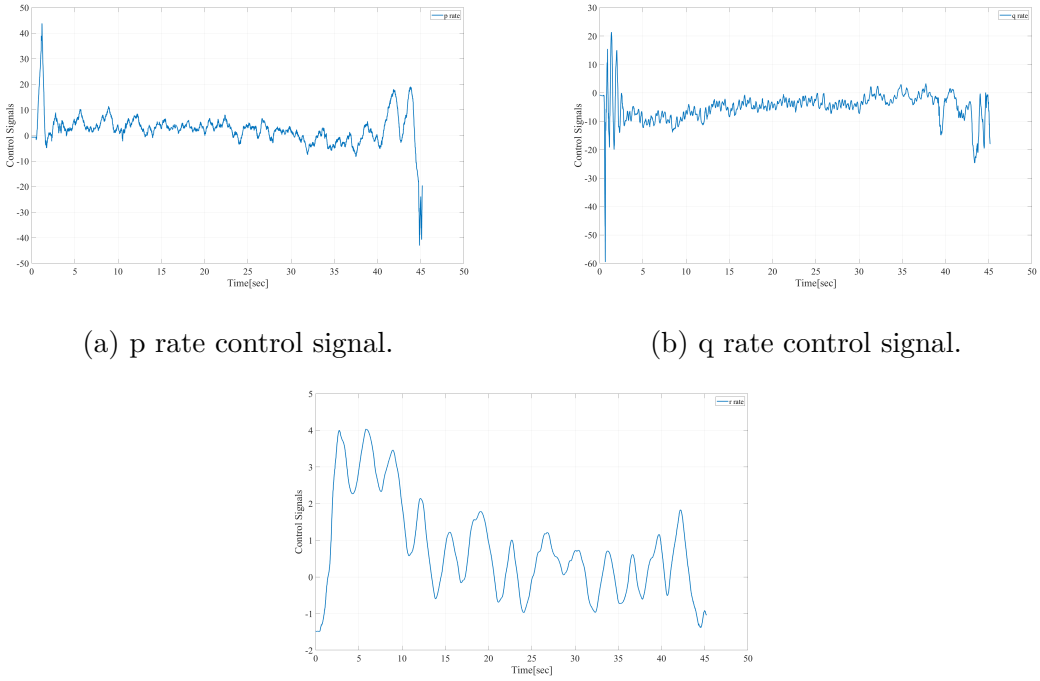


(b) v Velocity.

Figure 7.74: u, v velocities.

From XYZ trajectory tracking and u and v velocities, it is seen the motion that is performed by the aircraft bounded to small movements, consider as a drift oscillation.

-Control Signals

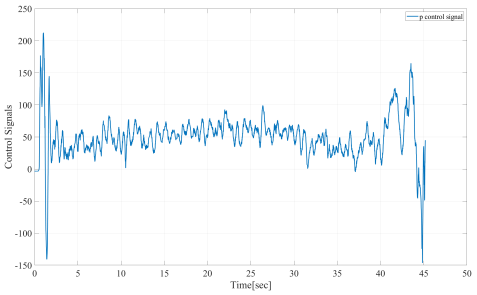


(a) p rate control signal.

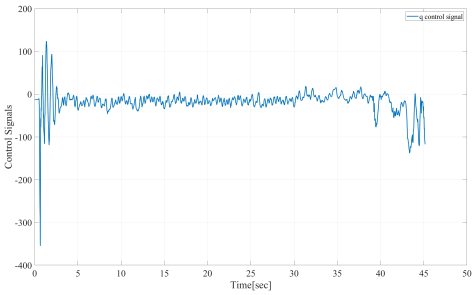
(b) q rate control signal.

(c) r rate control signal.

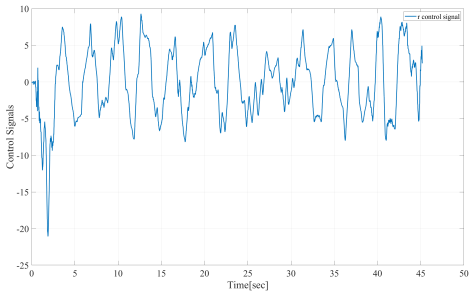
Figure 7.75: Desired angular velocity p, q, r of convertible tricopter hover experiment.



(a) p control signal.



(b) q control signal.



(c) r control signal.

Figure 7.76: Angular velocities Convertible Tricopter Hover Experiment.

Data from Figures 7.75 and 7.76 are the steady signals to stabilize the system, those that are induced to the system as characteristic, used as filter information for other experiments, as well as steady performance analysis.

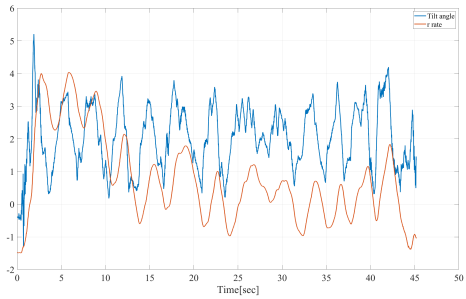


Figure 7.77: Tilt angle (δ) vs r rate control signal of hover experiment.

Data obtained from this graph allow us to recognize that the system has a coupling of tilting mechanism angles with the r control signal, applicable when is

not a positioning scheme, when presented it would be another element sum to this angular term.

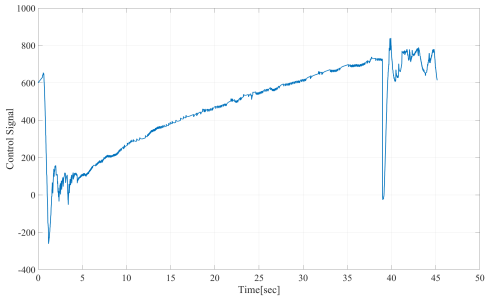
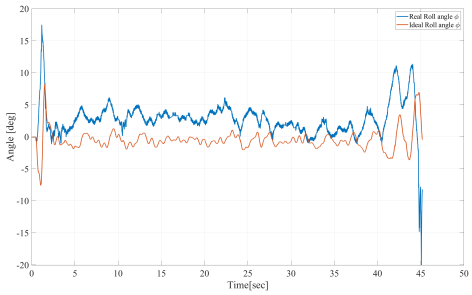


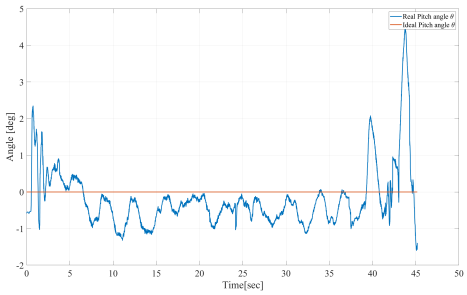
Figure 7.78: Thrust Control Signal.

The integral term is described in that graph, which would allow us to consider endurance and recognize the effects due to the taking off and landing process for this specific aircraft.

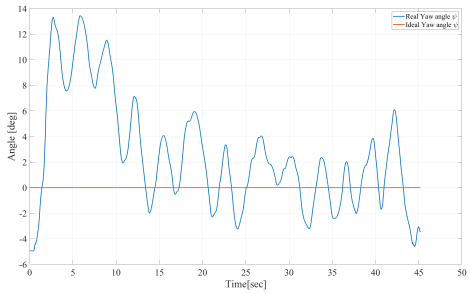
-Attitude



(a) Roll angle.



(b) Pitch angle.



(c) Yaw angle.

Figure 7.79: Attitude angles of convertible tricopter hover experiment.

Attitude angles of this system on steady hover show a system with a tendency of zero angles, with a small error and oscillation, drift of 2°, and an offset on the roll, which is mitigated by the system when the integer is loaded.

7.2.5 Point tracking: linear movement

This experiment is designed to evaluate movements on one axis, overshoot, and establish time. A linear trajectory of 3m is established, with the main objective to have control of the whole step.

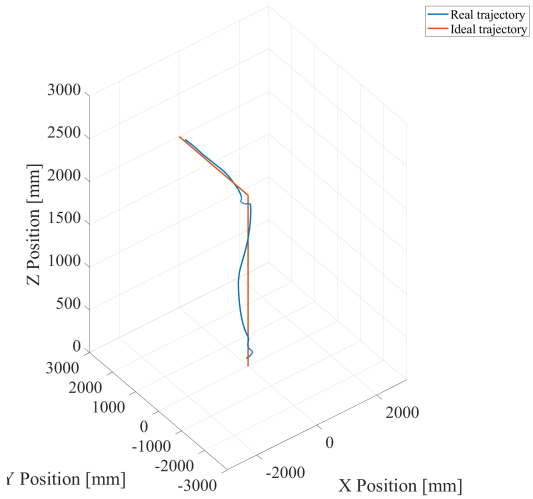


Figure 7.80: XYZ trajectory tracking, real vs ideal.

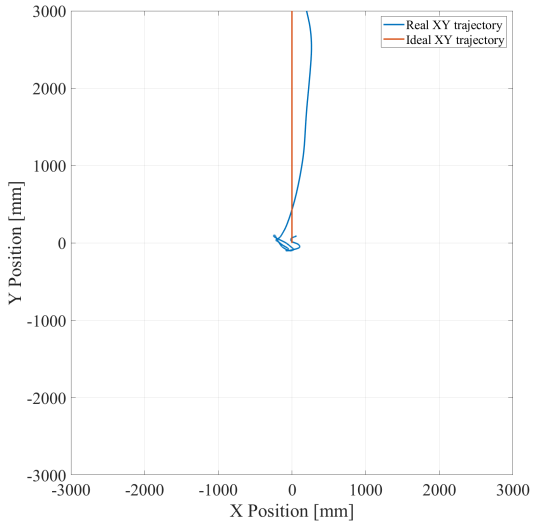
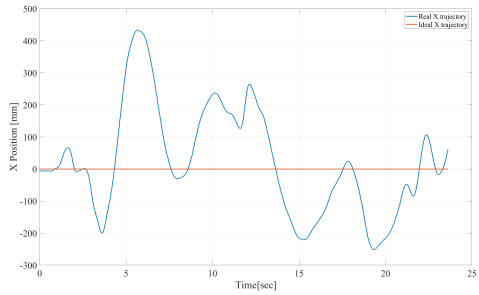
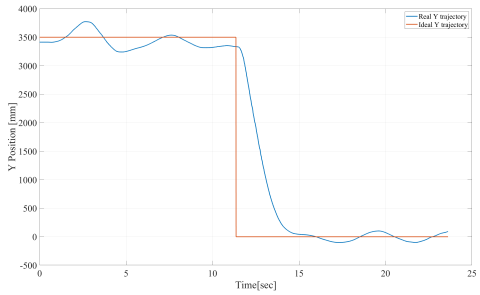


Figure 7.81: XY trajectory tracking, real vs ideal.

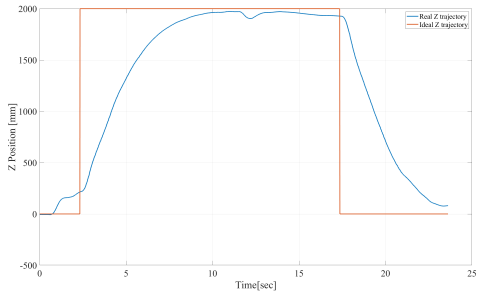
The trajectory tracked from this experiment shows us important results, from beginning the take-off process induce a position error, which was held by the aircraft and tried to correct, but as the trajectory starts before its stabilization it creates a 300mm error from linear movement, is important to also consider that this error should be corrected if the experiment has lasted longer, but for this case, the main objective is to observe the behavior of the aircraft at those fast changes.



(a) X trajectory tracking, real vs ideal.



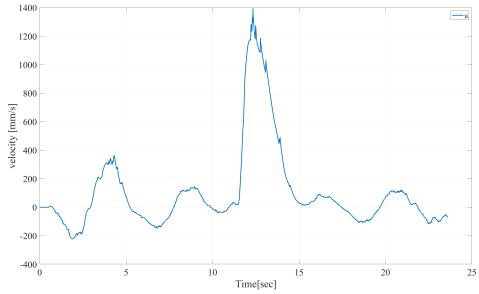
(b) Y trajectory tracking, real vs ideal.



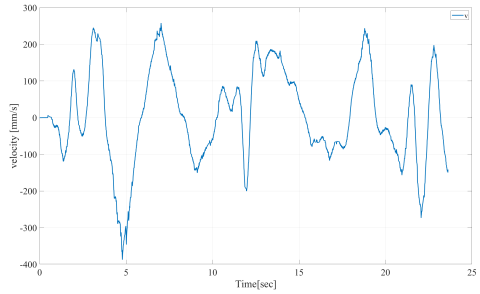
(c) Z trajectory tracking, real vs ideal.

Figure 7.82: X-Y-Z vs Time trajectory tracking

The experiment was held at the "Y" axis, in that sense the graph paid attention to Figure 7.82b, visualizing the step response of the system, important to mention that this behavior is not linear.



(a) u Velocity.



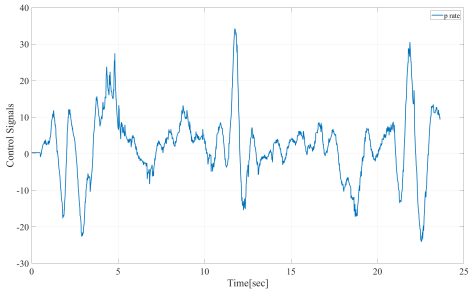
(b) v Velocity.

Figure 7.83: u, v velocities

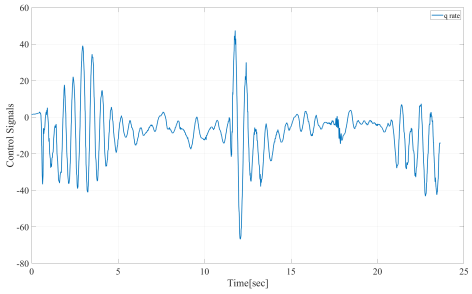
For this specific experiment, it is required u velocity of 1.4m/s, that for an

instant of time, is developed at a short trajectory and used to prove that the system could hold them and still at hover phase, in other words, is not required an established time between phases for this kind of movements.

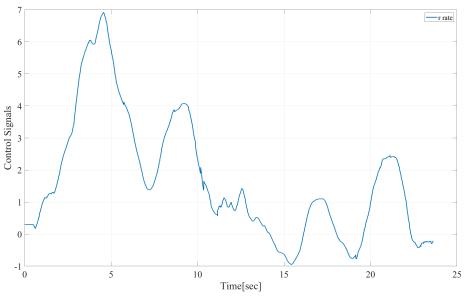
-Control Signals



(a) p rate control signal.



(b) q rate control signal.

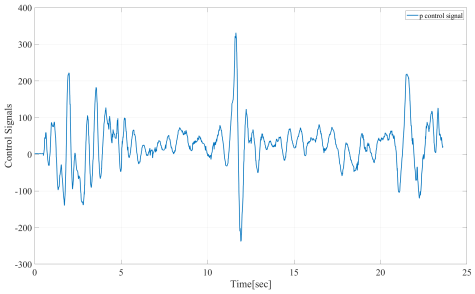


(c) r rate control signal.

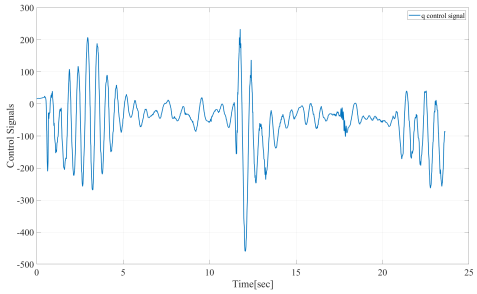
Figure 7.84: Desired angular velocity p, q, r of convertible tricopter point tracking experiment.

In this case, control signals show us the behaviors of the system with this kind of movement, from take-off at first 10 seconds, and the step response from 10 to 15. Important behaviors were acquired with pqr signals, first one is related to the first phase which was a fast take-off maneuver, inducing an oscillation on the whole system that should be dissipated, most of those behaviors are related to electrical disturbances, and rotors timing, all of those phenoms induce a difference on forces at the beginning, those initial conditions would be dissipated and denied by the system if a correct time for stabilization is performed. As second phase it is the step response, showing an interesting behavior, the inclusion of tilting rotors allows us

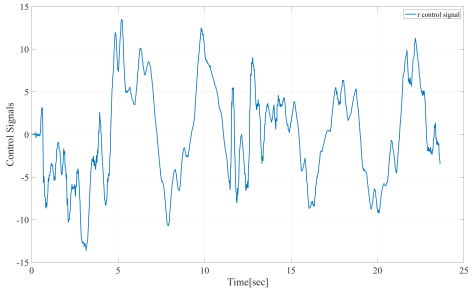
to require low signals for those fast changes movements, in orders of hover-denied disturbances, the other control energy is performed by the tilting mechanism that steers the propulsion to the direction required.



(a) p control signal.



(b) q control signal.



(c) r control signal.

Figure 7.85: Angular velocities Convertible Tricopter Point tracking Experiment.

On these signals, the behaviors are similar and non-disturbances were observed, becoming into induced signals from the other control layer.

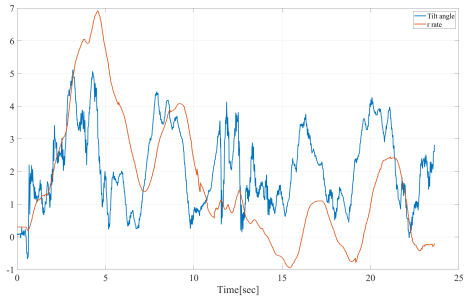


Figure 7.86: Tilt angle (δ) vs r rate control signal of point tracking experiment.

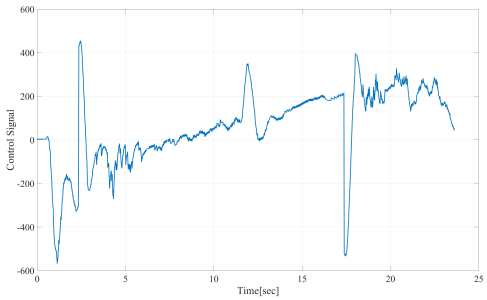
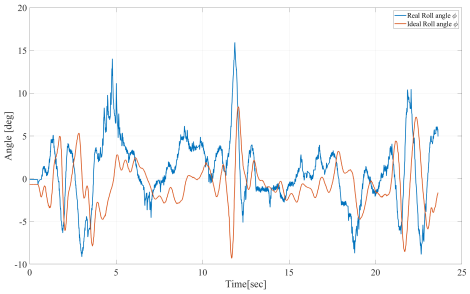
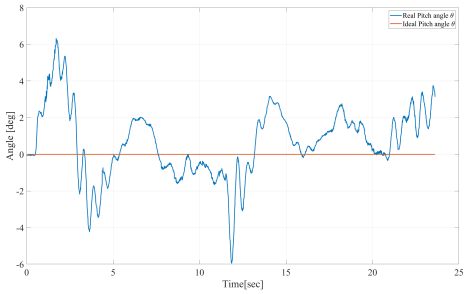


Figure 7.87: Thrust Control Signal.

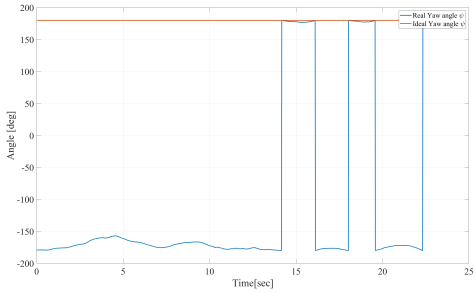
-Attitude



(a) Roll angle.



(b) Pitch angle.



(c) Yaw angle.

Figure 7.88: Attitude angles of convertible tricopter point tracking experiment.

These orientation angles show an expected behavior feed by position scheme, some points to highlight are related to pitch angle which should decrease, but for this fast change maneuver is acceptable, and consider as a nonideal change of phase; another point to mention is related to yaw angle, which has changed from 180 to

$-180°$ becoming into points that are considered as the same point, just numerical noncontinuous.

7.2.6 Tilting Ramp

The experiment was controlled with an input of initial tilting angle (δ) of zero and increasing them to 45° , at the end it suddenly stopped, but for analysis purposes is not presented the final phase, to have clear data to visualize from the straight flight.

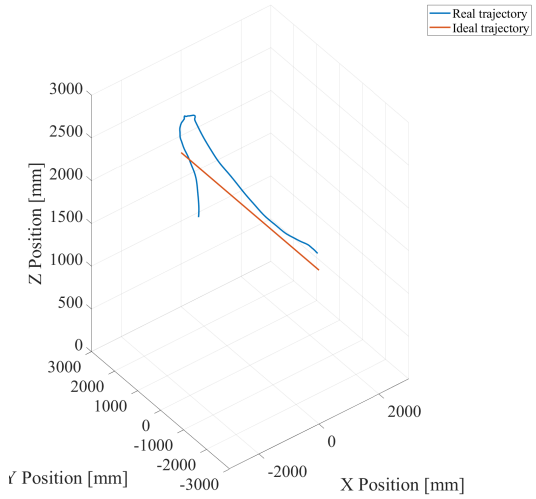


Figure 7.89: XYZ trajectory tracking, real vs ideal.

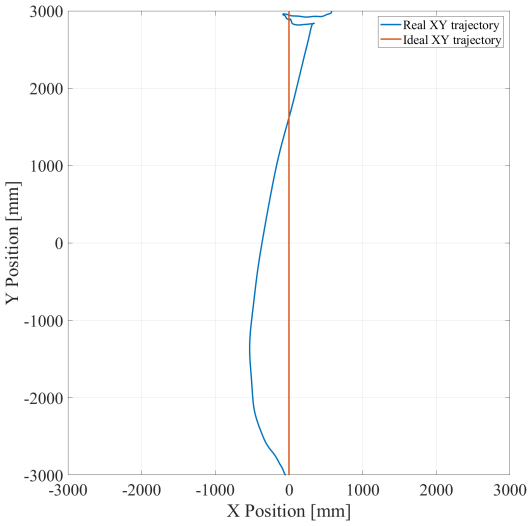
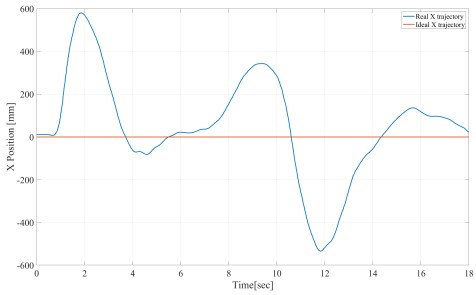
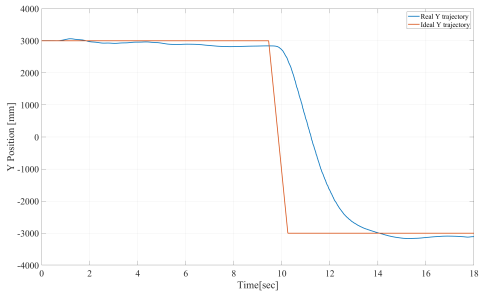


Figure 7.90: XY trajectory tracking, real vs ideal.

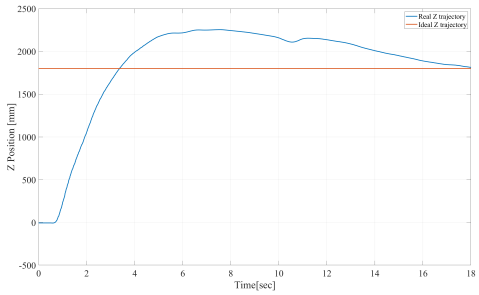
It is developing a flight of 6m, this accomplishes by the aircraft, errors are induced due to the initial error at p, which tends to create a disturbance that was not possible to dissipate at the beginning due to the other control signals required to perform the flight.



(a) X trajectory tracking, real vs ideal.



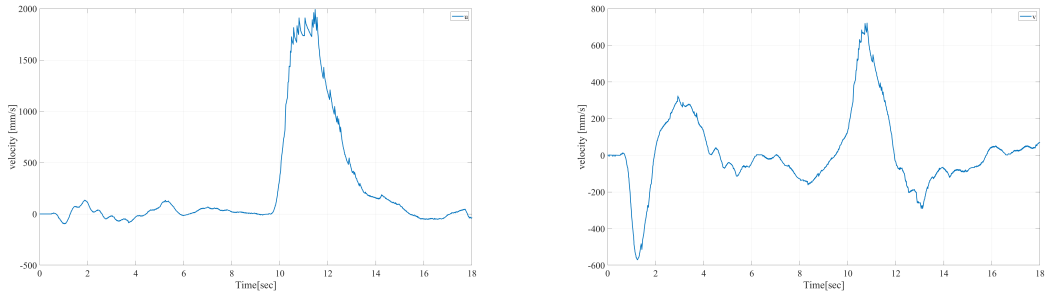
(b) Y trajectory tracking, real vs ideal.



(c) Z trajectory tracking, real vs ideal.

Figure 7.91: X-Y-Z vs Time trajectory tracking.

From the signals obtained it could be concluded that the system was excited at 9 seconds hold them for 1 second and keep out that signal, which produce a strong response from the system trying to accomplish that input, in that sense is required to have a specific tune for the positioning layer, which would recognize that specific cases to produce a correct output but at the same time guarantee the stability of the system.



(a) u Velocity.

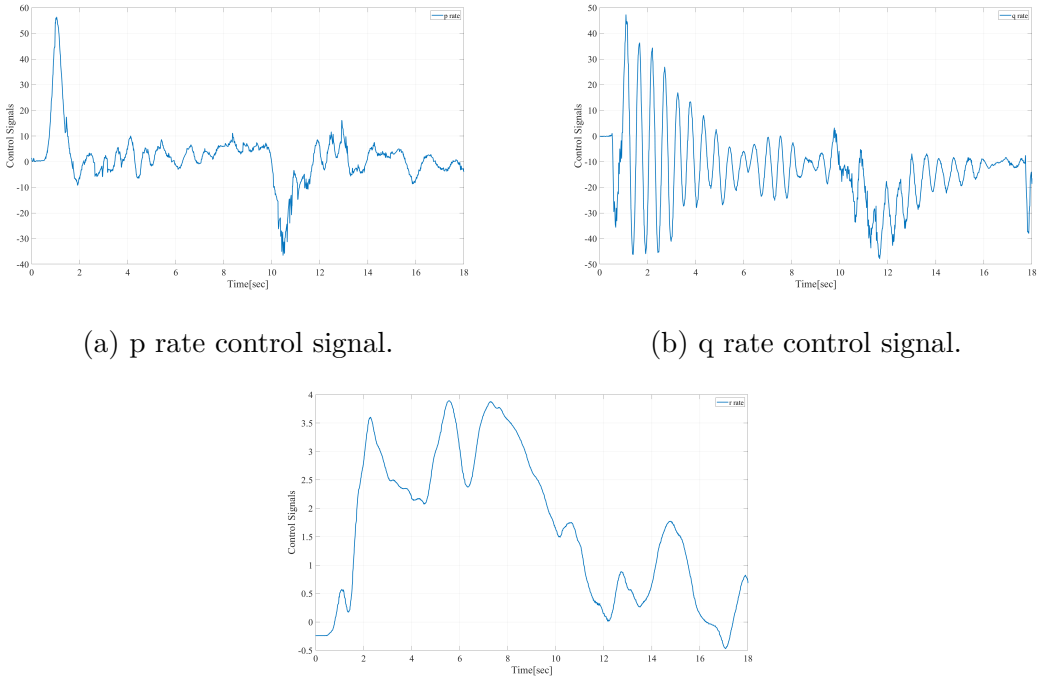
(b) v Velocity.

Figure 7.92: u, v velocities

Form linear velocity is observed that the system holds 2m/s for 2.3 seconds to accomplish the mission, in this case, the first oncoming of the system capabilities, it is observed the influence of the structure on this kind of straight flight.

-Control Signals

From control, the field is expected to visualize a behavior on a system with a high input at the stabilization phase, in that sense oscillations are presented.

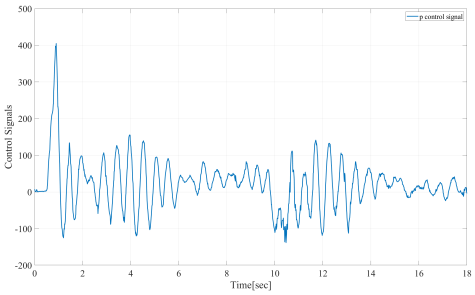


(a) p rate control signal.

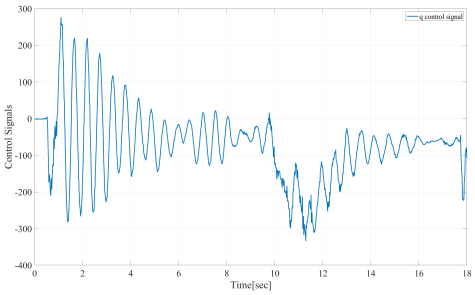
(b) q rate control signal.

(c) r rate control signal.

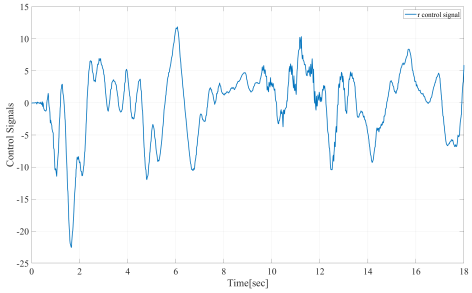
Figure 7.93: Desired angular velocity p, q, r of convertible tricopter hover experiment.



(a) p control signal.



(b) q control signal.



(c) r control signal.

Figure 7.94: Angular velocities Convertible Tricopter Hover Experiment.

Both control layer shows the same behavior, with the highest control signal use until now, and an initial high amplitude, which was already clarified.

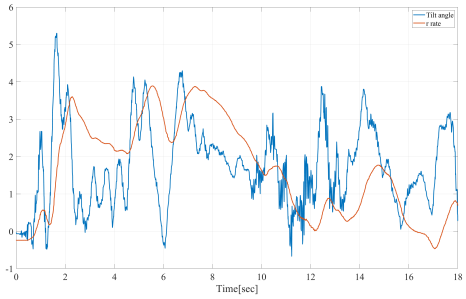


Figure 7.95: Tilt angle (δ) vs r rate control signal of tilting ramp experiment.

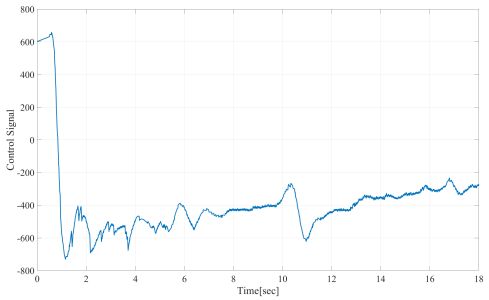
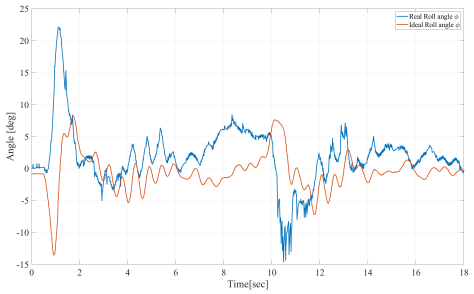


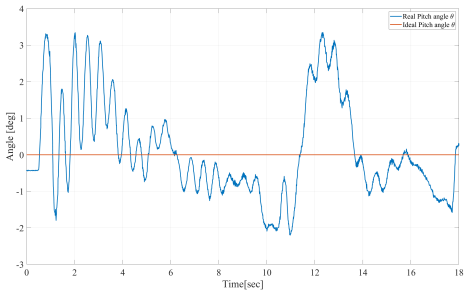
Figure 7.96: Thrust Control Signal.

An important behavior is obtained from this thrust graph, the experiment of high response is set from 8 to 10 seconds, for this case the signal stays similar on the whole process, which means the force induced by the wing was in balance with the increase required by the system, but once the requirement is over this force stills present, which correspond to a decrease on signal to maintain the system at the same height, proving the efficiency of this configuration, which also leads to new challenges, this system should be prepared to counteract these effects for cases where it is necessary to change phases.

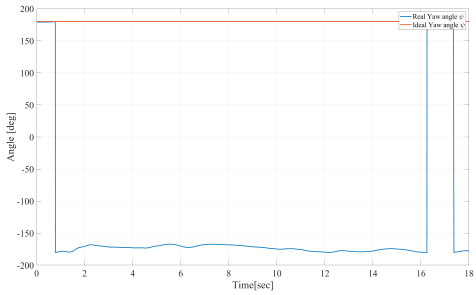
-Attitude



(a) Roll angle.



(b) Pitch angle.



(c) Yaw angle.

Figure 7.97: Attitude angles of convertible tricopter tilting ramp experiment.

From this angle, visualization is observed that the system maps the input signals and maintained the system on operation bonds.

7.2.7 Fast line

Those experiments were designed to evaluate the u velocity produced, bounded by the limitations of the effective area in the laboratory. To develop these experiments the system feeds it with u velocity as desired value, other aspects are considered as dependent on them, absorbed by the scheme presented.

7.2.7.1 Experiment 1

As the first experiment is required 2m/s as u velocity, already used in previous experiments, for reference use.

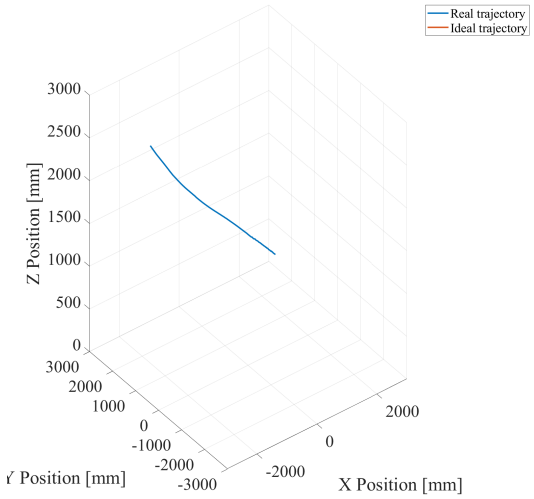


Figure 7.98: XYZ trajectory tracking, real vs ideal.

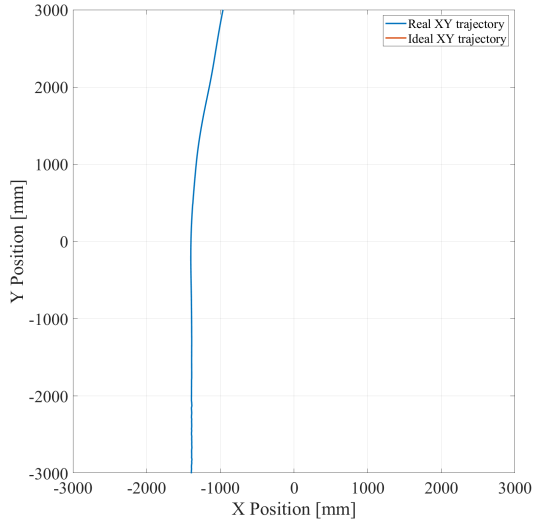
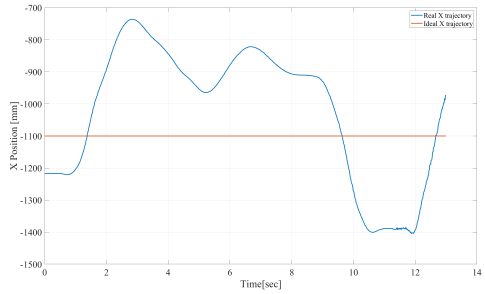


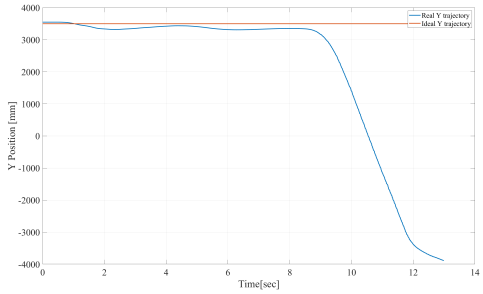
Figure 7.99: XY trajectory tracking, real vs ideal.

As seen in those graphs, the position is not the first parameter to be controlled,

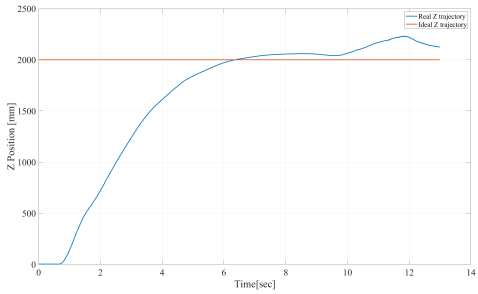
drift is allowed for those experiments. It used the 6m space available for the whole experiment.



(a) X trajectory tracking, real vs ideal.



(b) Y trajectory tracking, real vs ideal.

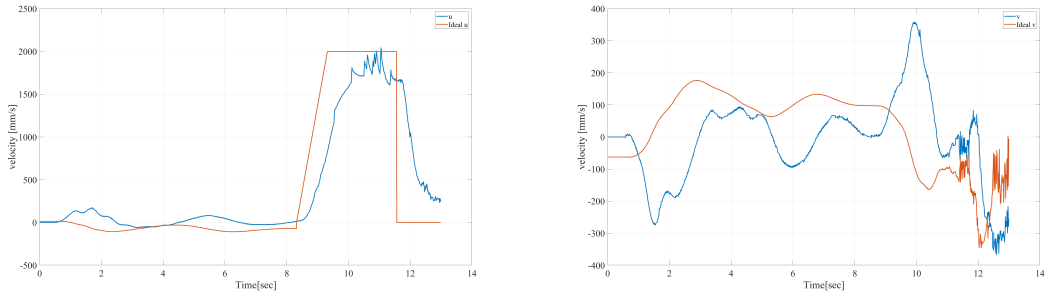


(c) Z trajectory tracking, real vs ideal.

Figure 7.100: X-Y-Z vs Time trajectory tracking.

Important points to mention in this scope, are that position references are fixed, but are not used for the position controller input, in that sense, use those plotted signals as just a visual reference, not the actual data desired.

From the data analysis, it is concluded that the system is excited in such ways that have wider errors, with an initial error that on those strong tests would be tried to correct but the response is higher than expected getting as result an error of 800mm which it is considered as the straight level flight it should be corrected in a couple of seconds if it were plenty of space, for y is a different behavior, which was used as test axis, creating a ram behavior. From z data it should be considered that at the final stage it was inducing force to the system that is reflected in an increase of that position, on the longest transition time it would not be a problem for the system, and the control scheme should have a response enough to consider that aspect.



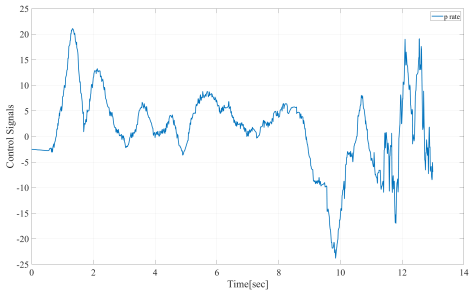
(a) u Velocity.

(b) v Velocity.

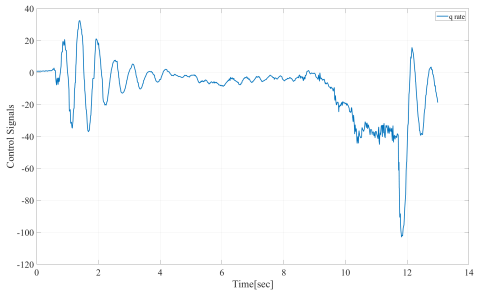
Figure 7.101: u, v velocities.

The u velocity is evaluated with feedback reference in that sense the system reaches that references and it were flyaway to not exceed them by that reason this behavior is presented, but as average signal it is possible to say that the system could hold them.

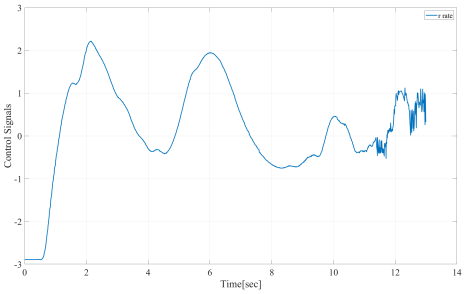
-Control Signals



(a) p rate control signal.

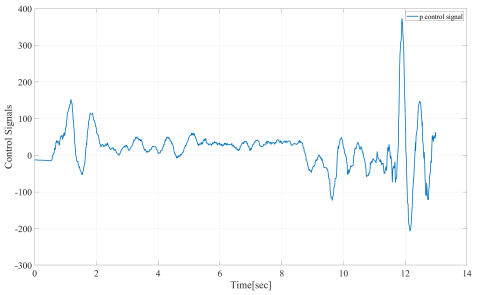


(b) q rate control signal.

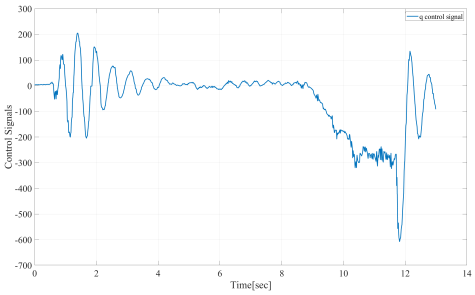


(c) r rate control signal.

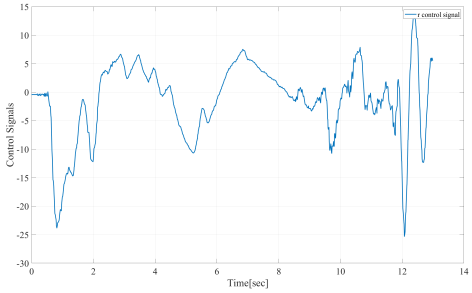
Figure 7.102: Desired angular velocity p, q, r of convertible tricopter fast line 1 experiment.



(a) p control signal.



(b) q control signal.



(c) r control signal.

Figure 7.103: Angular velocities convertible tricopter fast line 1 experiment.

This experiment barely analyzed these signals due to its behavior; it performs similarly to in hover, and the control effort was absorbed by the tilting mechanism becoming into low magnitudes signals.

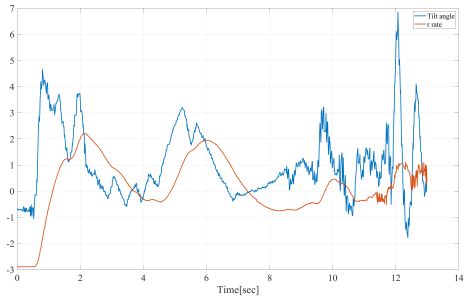


Figure 7.104: Tilt angle (δ) vs r rate control signal fast line 1 experiment.

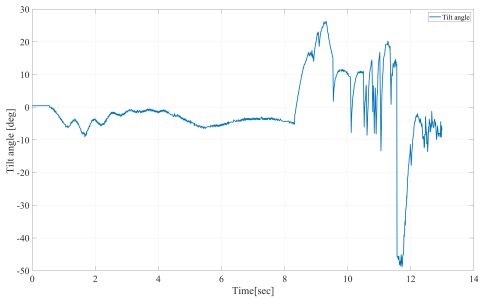


Figure 7.105: Tilt angle main control (δ_{master}).

With this graph it could visualize how the system reacts to that input of the desired velocity, requiring a tilting angle of 20° on average, and having a wider area of operation for high-speed flight.

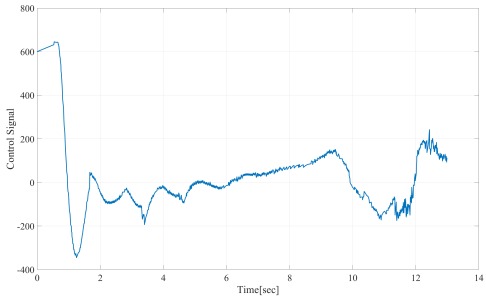
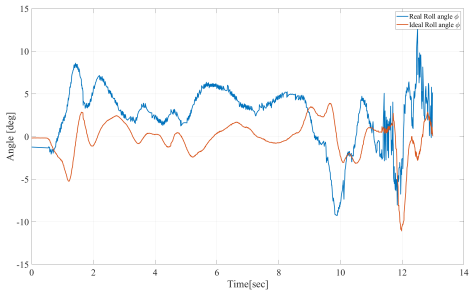


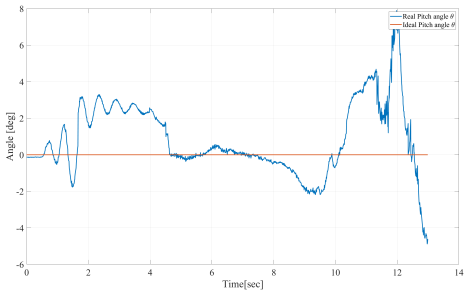
Figure 7.106: Thrust Control Signal.

In this case, it is observe the influence of the wing on the thrust signal required, at the beginning of the trajectory it required some amount of energy to hold the system, but when it start gaining speed it decrease, 200 units for this case, at the higher velocity it could hold the whole system with no influence of the rotors energy, used it just as horizontal propulsion.

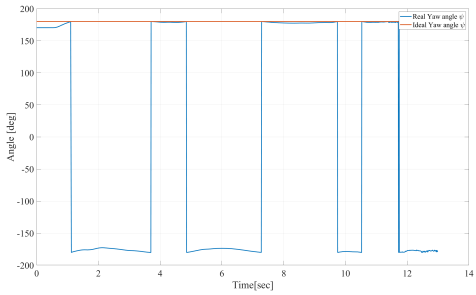
-Attitude



(a) Roll angle.



(b) Pitch angle.



(c) Yaw angle.

Figure 7.107: Attitude angles of convertible tricopter fast line 1 experiment.

These angles presented show a clear map behavior, but other elements are also inducing them to have other angles, in that sense it is applied a more aggressive control scheme or including those other forces that could be improved that error that for this case are up to 5 deg.

7.2.7.2 Experiment 2

This is a partial experiment, it was designed with the desired velocity of 5 m/s, but for that magnitude, it is required a longer laboratory, which forces us to evaluate the system with that consideration in mind, for analyzing purpose it is performed but is stopped when a collision is imminent.

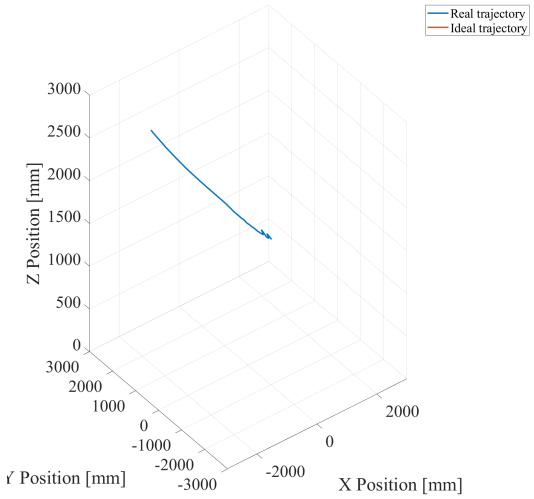


Figure 7.108: XYZ trajectory tracking, real vs ideal.

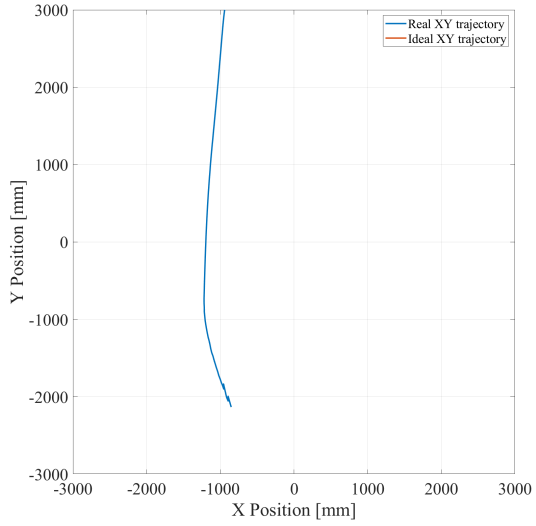
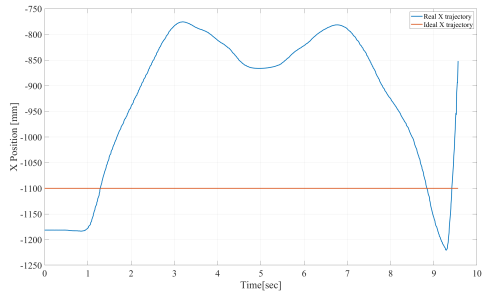
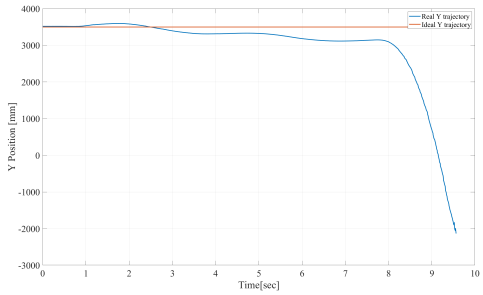


Figure 7.109: XY trajectory tracking, real vs ideal.

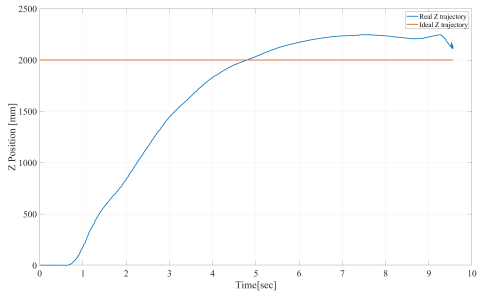
This trajectory is like the experiment presented before, which allows us to mention that is a tendency to perform that kind of movement with these inputs.



(a) X trajectory tracking, real vs ideal.



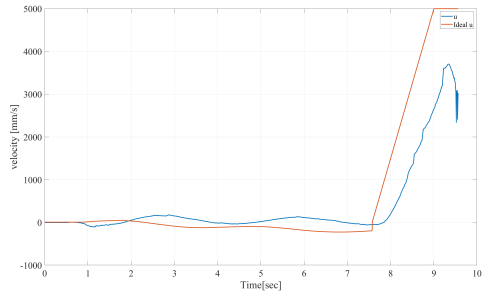
(b) Y trajectory tracking, real vs ideal.



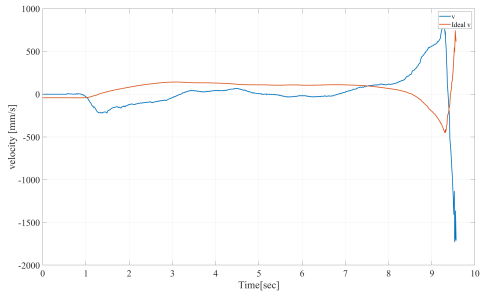
(c) Z trajectory tracking, real vs ideal.

Figure 7.110: X-Y-Z vs Time trajectory tracking.

The magnitudes develop in this experiment are also consistent with the first one.



(a) u Velocity.



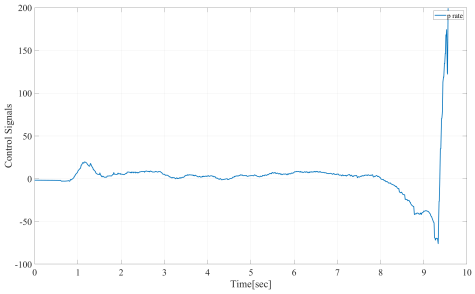
(b) v Velocity.

Figure 7.111: u, v velocities.

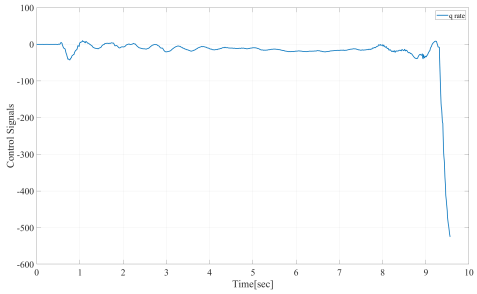
The important topic to analyze in this case is u velocity, which at the final time it developed 3.5 m/s just stop it by the collision avoiding, with those values it

is possible to mention that the system response was according to the input signal just delayed by physical aspects.

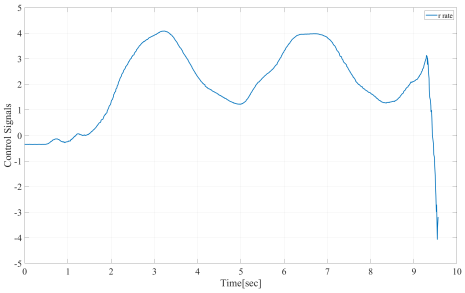
-Control Signals



(a) p rate control signal.

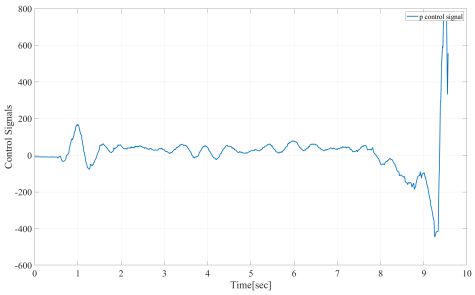


(b) q rate control signal.

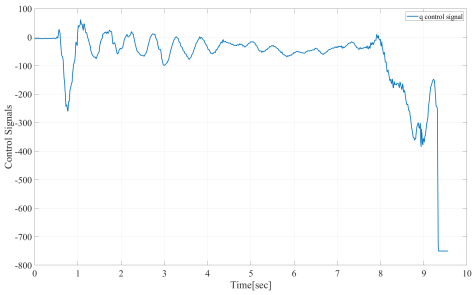


(c) r rate control signal.

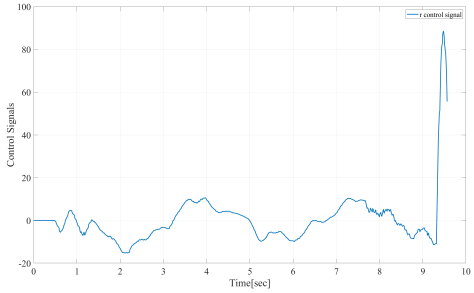
Figure 7.112: Desired angular velocity p, q, r of convertible tricopter fast line 2 experiment.



(a) p control signal.



(b) q control signal.



(c) r control signal.

Figure 7.113: Angular velocities Convertible Tricopter Fast Line 2 Experiment.

For control signals it is recognized that the system was working with low magnitudes, becoming a great response, on the other hand, it is the final response, which was developed to have an emergency stop.

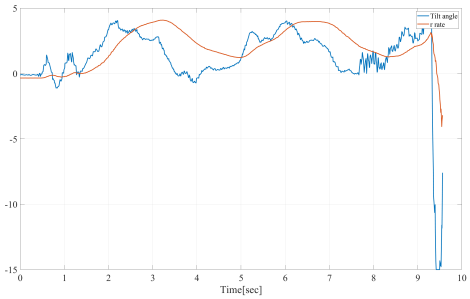


Figure 7.114: Tilt angle (δ) vs r rate control signal of Fast Line 2 Experiment.

In this case, is important to mention that the system was also inducing a δ angle to counteract the effect on r.

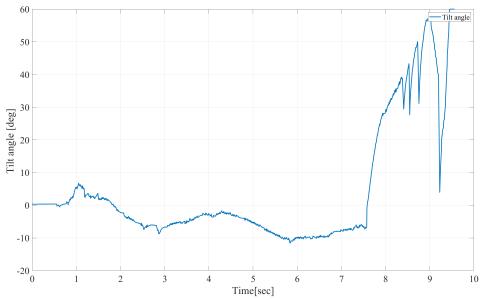


Figure 7.115: Tilting angle main control (δ_{master}).

As for the total tilting angle, the system uses fifty deg as the maximum, due to the fast response required to perform this trajectory, if it is held it could be changed to a total straight flight phase. In the analyze this signal presents the influence of the tilting mechanism on the final movements of the aircraft.

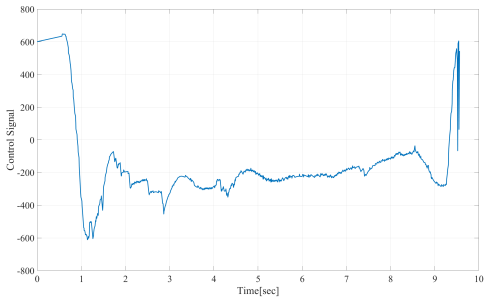
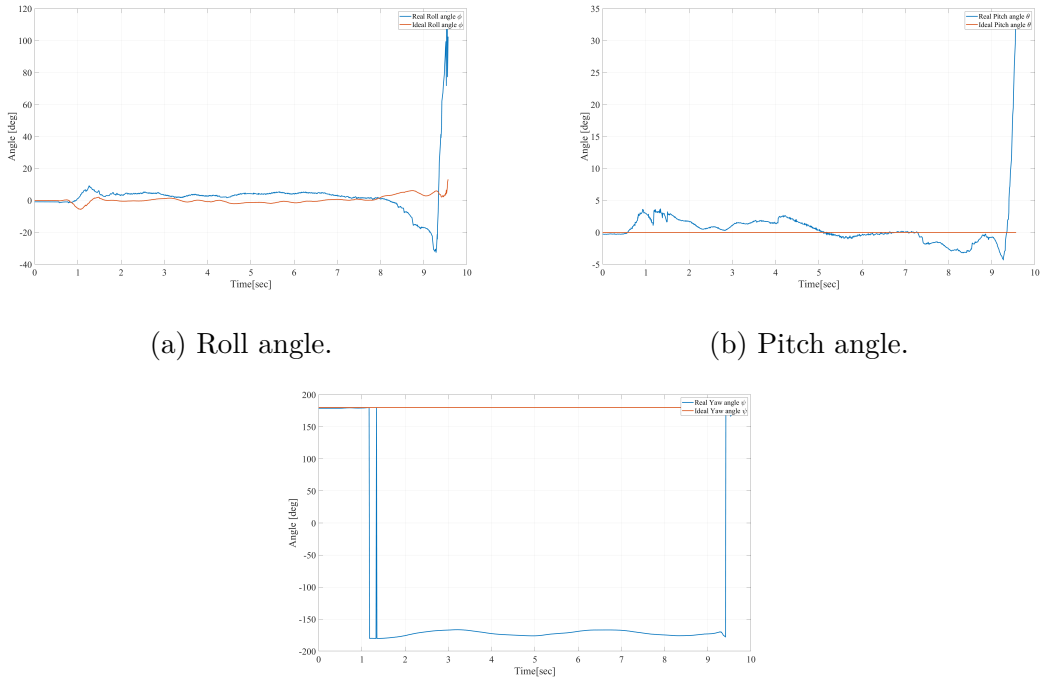


Figure 7.116: Thrust Control Signal.

-Attitude



(a) Roll angle.

(b) Pitch angle.

(c) Yaw angle.

Figure 7.117: Angle orientation Convertible Tricopter Fast Line 2 Experiment.

In this specific case, the angle performs better than the other case, due to better initial conditions, just at the final stage, the system uses a high-value angle to induce enough drag to stop the aircraft.

Chapter 8

Discussions and Conclusions

8.1 General Objectives Accomplish

Our main objective is related to the design and manufacture of a convertible UAV platform, which accomplishes both kinds of missions, hover and high-speed flight.
In addition auto sustainability is included in this model, in that sense, all of the design parameters were developed having a model that performs that kind of flight test at hover and cruise modes, and auto sustainability is partially tested. The influence of the wing is highlighted in the experiments; however, due to space and tracking limitations, was not tested at full operation. Finally, the aircraft is capable of developing the expected capacity since, even with limited inputs and short flights, a profound influence of the lift force on the system is observed, which is extrapolated to operations conditions, which predicts that its operation will be reached.
As a synthetic result, it accomplishes our objective.

8.2 Discussions

Our development found that it is possible to design and manufacture a small-size convertible UAV, important data is conducted with this investigation, from the methodology for the design of an unconventional aircraft to dynamics related to these configurations.

With those elements mentioned before it is possible to discuss individual parameters that were conducted by the results. From methodology, design, and development of prototypes, there are important results, which are related to relations, limitations, and selection parameters to consider in this kind of development. Our case is special in terms of the methodology used for that development, where it was selected to divide the whole project into three related projects that create considerations for each stage; in that sense topics from control, materials, manufacture, signal processing and other elements are developed and related to the entire system. It was used a well-known configuration for the initial developments, which is a quadrotor structure, implementing the control scheme, avionics systems, power units, propulsion, and manufacturing techniques.

This first stage of aircraft development allows us to have a tested system that is under similar loads and materials implementations, with that considerations are tuned components and schemes that are used in the following steps.

A quadrotor configuration based on additive manufacture and multi-materials components is developed, and main objectives are accomplished, especially those related to good performance flight and modular implementations, which are directly exported to the final prototype. This aircraft is tuned in orientation scheme with performance comparable to commercial aircrafts, angular errors of $0.5°$, provide avionics system that is precise enough for other implementations. It this case for the final prototype; an important point of this is related to programming paradigm, on commercial developments it is not open source, which in other words, it means that it is not configurable by the final user. On most applications is not a problem, but on

a newer configuration is not possible to use them; for that reason it is important to use our development, evaluated at this stage.

As a small-size configuration there are some parameters to evaluate the system; authors mention that its angular error should be less than 2° and in navigation scheme, it must have less error than its maximum physical diagonal, for this case 400 mm, [62]. All of those considerations mentioned by the authors are accomplished and overcome in this system, performing precise flight; another parameters of evaluation mentioned at literature are energy base [20]. For this multirotor configuration is mostly evaluated by control signal minimization, where a noninvasive and stable output is ideal; also endurance is mentioned; it this case is not evaluated with different power units for energy evaluation, just evaluated with its selected battery that performs an average of 10 minutes of flight with active tracking, more than other systems. Some confusion is also presented due to evaluation in hover endurance which in this case is not presented by that reason is not mention a comparative of this parameter where other aircraft holds flights of 30 minutes.

Other elements implied in this development are related to the GNC scheme use, designed according to the configuration of the aircraft. For the UAV control architecture and proposed missions, we developed real-time validations that allow us to verify the correct behavior of the scheme with equations of motion, references frames and control strategies to relate the control layers. This part used a generic configuration, which allows us to use the whole development with minor changes, especially on the orientation layer, by that reason, reference frames are established using the NED scheme and aligning all of them to a general configuration.

At presented literature, the methodology followed by authors to design and manufacture quadrotors is proposed in [12] with acceptable results, and also they evaluate the architecture [50] and flight controller techniques [25]. Their specific mission is accomplished, however, there is a difference in the model proposed in this thesis project. This could hold similar results as their prototypes but also including flexibility and low energy implementation, seeking for efficiency. In that sense, this implementation uses a simpler control scheme than those presented in the literature

of aircraft control, minimal energy use by control and computational domain.

The second stage of this development involves the analysis of convertible structures with limited dynamics; in other words, it was designed a model which is focused on the convertible scheme with no influence of other elements. In this case, fixed-wing structure induces behaviors which are complex to understand and other variables to analyze. This implementation of an actuator on arms axes allows us to test and tune a convertible aircraft, which has an over-actuated system. For that reason, a mixing matrix of dynamics/control outputs is proposed; a usual behavior of convertible aircraft is that the system is tuned for specifics missions, and a combination of actuators, as known as tilting mechanism and rotors, give specifics behaviors. For this case it is selected a combination that is created for pitch-less flight, acceptable performance is developed and dynamics are mitigated by the system control scheme used. Another topics to discuss in this stage are related to materials selection, which is important for structural integrity, for that reason simulated and validate multiple iterations of system implementation, using geometric optimization as well as the advantage of the properties of materials and their manufacture, the anisotropic behavior of AM is consider and use for forces distribution, creating a system that is optimized for its dynamics and a lightweight implementation.

Establishing those parameters and performing validation tests are discovering and mapping those dynamics, response times, and structural implementations required for this kind of implementation. That data is developed in the third stage of this work, where the whole dynamics, system configuration, and control schemes are considered giving as a result the main objective accomplished, a convertible aircraft with fixed-wing structure.

The final prototype is made employing the set of parameters found previously, as well as the implementation of the aerodynamic aspects, material characteristics for internal geometry, and model base dynamics for feedback of the system at the control field. Results shows important data, from a fully base body on fixed wing that is ideal for auto-lift at straight flight, high-lift airfoil implementation is used, also damping effects on maneuvers are presented; using results it is concluded that this

structure allows us to have a hybrid aircraft, capabilities from multirotors and fixed-wing. U and V velocity graphs allow us to monitor aircraft velocity, at this point is already resolved from aircraft velocity vector at wind frame to body axes, with that considerations we are able to related the incident flow via aerodynamics angles, with that considerations is carry out flow velocity that is induced at the main wing, which is producing a force that is directly appreciated at the thrust graph which is decreasing while u velocity increase, demonstrating that this configuration works and it performs the conditions established in the proposed objectives.

From the results, it is visualized that this system performs both phases, hover using multirotor principle and cruise straight flight with the fixed wing and tilted rotors aligned to 90°. In hover phases is observed a huge influence of tilting mechanism that allows us to bound the system to pitch-less maneuvers, due to over-actuated outputs, more than one input perform same behavior at outputs. It is use two layers control, in orientation scheme, it give us acceptable results, for this case the whole interactions is absorbed on this layer, including inversion of dynamics and perturbations, it is verified at experiments presented for this convertible configuration, its results are similar to our quadrotor; 2° of average error is perform, it proves performance and capabilities at indoor precise flight. For cruise flight, it is perform a couple of experiment, bounding parameters to simulate them, on future works it would be tracked and reported, but its visual performance reflects that is capable of performing that phase of flight. As a final point, it is the conversion phase as it changes from one to another, on the fast line, tilting ramp and point tracking experiment are shown that the conversion phase, when is performed by a rapid change, it has low quality on Z accomplishing. However, it is bounded as initial conditions, only performing that experiments if there are enough space for them, and at the other ones that have a slow conversion phase is shown that the system absorb uncertainty, by that reason, it is tuned that behaviors on the control for future developments.

This design is hard to compare with other prototypes due to a non-established configuration, every researcher proposes his approach, using generic parameters as reported. Most remarkable authors [46][15][32] develops its configuration with ac-

ceptable results. The main difference with these is that our system performs with a low energy approach, minimizes error and a configuration that allows us to have a transition between phases on every stage of the flight while they are limited to take off phase accomplish by the first author, just newer dynamics for the second mentioned before, and a configuration similar to our second stage at third one mentioned, but this one has just 3 rotors; in that sense, its capabilities are reduced due to a persistent signal for momentum stabilization, giving a reduced performance. On the other hand, it is the methodology used for control scheme selection; literature uses lots of techniques to stabilize the system [53], and most of them are computationally demanding. For that reason is proposed to use a more straightforward and classical approach, PID as the main control loop with dual layer implementation, using the whole sensor data for analyzing and controlling the system, developing a system that runs at 500Hz. Others implementations, as [7] runs at 200Hz, which is acceptable for normal quadrotors that have normal dynamics, but for a system that also induces other forces, as well as directional rotors forces, that implementations require more complex controls, those runs faster to mitigate these fast-changing dynamics. Each actuator creates dynamics, if the system has different outputs that accomplish the same degrees of freedom, it is select a mixing matrix where are selected the behavior expected and used by the system to perform some actions, using all of the actuators for the whole system is possible as [30], but it could lack performance due to different response times from the actuators, by that reason at this case are selected for each dynamic to absorb with an analysis of response time required to have the best performance. Also precision on actuators lacks the system; for this case, it is selected rotors for main orientation (pitch and roll maneuvers) due to a better performance on time response and tilting mechanism for dynamics that are slow and not high-risk.

Elements that are also analyzed and compared with literature and previous works are related to aerodynamics. This work presents two main points: first is related to the main structure, which is based on an airfoil with a high lift, as pre-

sented in [56]. It is used for automotive applications with acceptable performance; however, its design is based on human-operated aircraft, giving promising results in this application. Developing a wing capable of performing at low Reynolds numbers, sweep slope, and effective area of angles to develop. On the other hand, aerodynamics are the influences of propellers, especially in a system with a multirotor. In most applications, a fuselage having airflow interaction is estimated and mitigated by a control field [59], in our case, it is isolated by a correct distribution of the system rotors, becoming into a passive and effective method to eliminate that disturbances. Our findings prove that it is possible and efficient to develop a convertible UAV that could perform a variety of missions and introduce newer capabilities. On the other hand, it also discovered aerodynamic interactions between configurations used, control schemes necessary for this kind of configuration, and signal processing algorithms for AHRS.

8.3 Conclusions

In this research project are developed multiple conclusions and general inferences, main object of study is the convertible UAV, specifically our setup. The results makes evident that performance is acceptable and it handle missions with the proposed configuration. Also it is validated the wing performance that induces lift force even if it is tested at low velocity; tilting mechanism allows us to have directional thrust parameter which was also tested and effectively implemented becoming into a great contribution for multirotors scope. Summarizing those parameters mentioned before is concluded that this configuration accomplishes the objectives propose and allow us to develop future developments.
For better visualization of conclusions, these are enlisted below with a chapter organization.

- Theory of UAV: each author proposes its configuration, with a variation on structure, rotors placement, number of them, methodology of implementation, geometric distribution, aircraft mass, endurance, and mission application. For that reason, it is established that depending on its objective it performs better than others on that specific point, in the convertible field. Proposing different configurations with dynamics variations, signal processing and mixing scheme, and performing different with a similar physical structure. For that reason, there is a huge quantity of configurations on this convertible field it is important to perform different schemes, with acceptable quality, and non-over-engineering platforms. On the other hand, there are the aerodynamic effects that are involved with aircraft, especially UAVs, concluding that there are forces that interact with aircraft, wind directions, and transition disturbances, encompassing. Foil theory deduces that there is a huge quantity of configurations and those engage in environmental effects which depend on configuration parameters making each structure different with different behaviors.

- Design proposal: In this section 3 stages are presented of the project. The quadrotor one, it is deduced as a conventional configuration that allows us to test other parameters that are required by the final prototype. However, in its development, it is addressed some important topics that allows to conclude for this stage that there is a synthetic methodology to design small aircraft, characterize and implement it, for this work is propose our methodology, also AM is validate as a technique to manufacture these configurations.

  From the second stage: there are important findings, tricopter configuration is hardly demanding to structure. In that sense, the forces are applied as a beam with differential force applications, it also induces dynamics behaviors that are not shown in the static analyze. For that reason, it is important a correct structural design, concluding for this prototype that our propose accomplish with those considerations. Another topic to consider it is the material selection, same structure performing different with a slight difference of material properties, but also that aspect improve some behaviors, by that reason is propose a multi-material scheme which performs better than a unique material, results carry out by simulations and real-time validation.

  On the last prototype, there are important findings; first, one related to the whole structure, which was developed based on an airfoil excluding interference by fuselage or other elements. For that reason, selection section was the center of the investigation. A high-lift airfoil is proposed and tested with simplified terms, even though considerations assume this design performance is ideal for the established requirements. The selection methodology is based on comparing different airfoils, all from the high-lift family. In the end, it is concluded that a balanced airfoil with a wider application area is FX-63. Afterward, the selection is important to consider the manufacturing field. That reason is simulated and optimized to have the correct part. In this case, it is concluded that the main body is manufactured by ABS with a light structure methodology, creating a part that is designed by forces distributions and dynamics parameters accomplished as a result of a well-implemented part.

- Equations of motion: three systems were analyzed, and the relations were observed. An initial system of the quadrotor was used, considering its dynamics and disturbances. Two other systems were developed, including those dynamics related to the tilting mechanism and the influence of the structure on forces and momentum determination. As an approach, the generic multi-rotors model is used to determine these systems, adding those elements required to describe newer dynamics. Those elements are included and related to wing nature, concluding that this simplified version has enough elements and considerations to describe and control the system.

- Avionics: this section introduces mainly elements of signal processing and the MCU architecture, highlighting the angular estimation scheme, which is the principal topic of this section with the implementation of the Mahony algorithm and filtering process of RAW data, with those implementations improving the individual signals as well as the final AHRS. Most of the consideration is related to IMU signals, introducing first and second-order filters for its components, where is important computational time and signals mitigation, both elements used for its selections and tuning process, concluding that a fine output signal, with proper internal signals, allow us to have a well-implemented AHRS scheme which is directly reflected at system performance been the feedback node of them.

- GNC: the whole scheme is implemented in the 3 systems, which are similar in terms of architecture; some terms of dynamics are unique for each aircraft that establish different parameters schemes, and non-structure differences; main algorithm is based on dual layers controls, for navigation and orientation, those schemes allow us to have better performance than a simpler configuration and also introduce terms from sensors, with those schemes, the aircraft gets more accurate behaviors and mitigates disturbances, aspects that are important for this kind of system which has a grade of incertitude; Ii the other hand, it was selected this configuration of dual layer PID due to simpler computation which

is directly related to a system that performs quicker, with aspects mentioned before is conclude that this scheme absorbs dynamics from the 3 kind of systems and allow us to control it.

- Validation: This section is considered as an experimental test of the prototypes; there are a more comprehensive number of conclusions, especially by its behavior on diverse kinds of missions. For simplification, result interpretations are just reported quadrotor and Tricopter with fixed wing results due to similar behaviors with the system that only has a tilting mechanism.

  Multirotor approach showed interesting and acceptable results. In hover, it reflects a consistent response, with a maximum of 10 cm error, it is improved by the adhesion of more characteristics of the system as aerodynamics and electronics models that mitigate drift due to small uncertainty and noncontrolled elements. From tracking trajectories tests are carried out and results show the performance at low velocity if precision is required, a problem induced by the positioning scheme, tuning, and adhesion of elements that subtract control signals improve its performance due to less main control interference. An example is the altitude, which is hold by embedded systems eliminating the reference from position scheme, recursion and security are carried out, as well as performances improving quality in terms of external calculation and reliability. That conclusion is supported by orientation signals that map the desired with the real ones, in that sense, the system has the capability to track the desired signals.

  Promising results are obtained with the convertible UAV; i.e., the hover phase shows acceptable performance, and maneuvers are limited due to tilting mechanism resolution giving a response on XYZ with limitations on closed-loops with fast response. However, normal trajectories such as circles, infinities, and linear movement are developed, providing acceptable results. Analyzing data from control signals concludes that this system is performing its objective of reducing control authority by rotors, using a tilting mechanism to perform movements in terms of energy efficiency. It results in a system that requires

less energy to develop those actions. As mentioned, there are some resolution-related implications, but minimal energy consumption is not a big problem. Other aspects to mention are those related to cruise flights. In the experiment, the phase shows expected results; wing lift generation is presented. The thrust graph is shown a reduction in the control force required to lift the aircraft, the maximum velocity in those experiments is limited to 3.5 m/s, which produces results of 25%. Thus, the main wing produces that force and extrapolating is predicted that the wing force would hold lift.

Summarizing that conclusion is presume that the entire system has acceptable results, it performs trajectories proposes, wing structure inducer lift force, convertible phases are accomplished, avionics system performance allows stable flight, structural and material selection have operating margin for the most demanding maneuvers, the control scheme is also correct for these configurations.

8.4 Future Work

These convertible configurations are still in progress, missions proposed require more effective payload; in that sense, is required a more capable prototype, especially at hover phase, actually limited by rotors thrust; It is demand selection and design of an aircraft that holds the capabilities of the convertible UAV presented and additionally aptness of more endurance and more effective payload.

Another topic that is propose to develop is a continuous algorithm that allows a controlled transition phase and mission designs for convertible UAVs, it is seek reliability, repeatability and disturbance rejection.

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Autobiographical Summary

Edgar Ulises Rojo Rodríguez

Candidate for the degree of
Maestría en Ingeniería Aeronáutica
con orientación en Dinámica de Vuelo

Universidad Autónoma de Nuevo León
Facultad de Ingeniería Mecánica y Eléctrica

Thesis:
Design of convertible UAV with hover and cruise flight capabilities

The Ing. Edgar Ulises Rojo Rodriguez born on October 15^{th} of 1997 at Monterrey, Nuevo Leon, Mexico. Son of Gilberto Rojo Guerrero and Maria de la Luz Rodriguez Diaz.

He stared its bachelor at august of 2014, specializing at Mechatronics engineer in Facultad de Ingenieria Mecanica y Electrica of Universidad Autonoma de Nuevo Leon.

As part of his social service and professional practice was a member of the Advance Manufacture Laboratory of FIME-UANL, developing projects related to inverse engineering, precision measurements, additive manufacturing, and advance materials,

most of the projects was industrial bounding, some of which are manufacture industry as FEMSA, Johnson & Johnson, Optima, Magna Automotive and others.
Its bachelor's degree was obtained at 2019 June, with outstanding grade and developing the thesis of "Maquina de electrohilado asistida por manufactura aditiva".
Actually, is part of Navigation Laboratory at UANL, active member of this research group.