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DESIGN AND DEVELOPMENT OF AN UAV WITH HYBRID FLIGHT CAPABILITIES

MASTER IN OPTOMECHATRONICS

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Contents

Abstract

This work presents the modeling and control of the transition maneuver of a class of hybrid Unmanned Aerial Vehicle (UAV): the tail-sitter. The modeling considers aerodynamic terms whereas the proposed controller is designed with the aim of achieve a transition flight from hover to cruise mode and vice-versa. The algorithm is designed to be easily coded in a real tail-sitter platform, hence all the assumptions and considerations take into account the usually available states for UAV control. The key idea behind the controller design is the time-scale separation between UAV's attitude and position dynamics. With this in mind, we obtain a desired trajectory for the pitch angle, which is the responsible to achieve the transition maneuver. The controller design is based on Lyapunov's approach and linear saturation functions. Simulations experiments demonstrate the effectiveness of the derived theoretical results. Also, it is presented preliminary experimental results in a Tail-sitter UAV developed at the Perception and Robotics LAB at CIO.

To my family who always been there for me.

Publications

"Design of a simple controller for the flight mode transition of a hybrid drone", **A. Flores**, J. Sanchez, A. Montes de Oca, L. Arreola and G. Flores. Accepted article in the *Conference on Decision and Control (CDC).*

"Improvement in the UAV position estimation with low-cost GPS and vision-based system: Application to a quad-rotor UAV", L.Arreola, A. Montes de Oca, **A. Flores**, J. Sanchez, G. Flores. Accepted article in the *International Conference on Unmanned Aircraft Systems (ICUAS).*

"Low-cost multi-spectral imagery system for crop monitoring", A. Montes de Oca, L. Arreola, **A. Flores**, J. Sanchez and G. Flores. Accepted article in the *In the International Conference on Unmanned Aircraft Systems (ICUAS).*

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Introduction

The Unmanned Aerial Vehicles (UAVs aka drones) designs can be divided into two main types: fixed-wing and rotary aircraft, both have their respective advantages and disadvantages. For instance, fixed-wing UAV can achieve long-distance travel due to its propulsion system and aerodynamic surface, i.e. wings. Thus, the thrust force is used in its entirety for displacement, and to maintain in the air the fixed-wing aircraft uses the force generated by the air hitting the wing surfaces, called normally Lift force. On the other hand, their disadvantages are that they need a runway to take-off and landing, they also require a considerable area to perform maneuvers for their positioning and orientation. Since fixed-wing aircraft takes advantage of the force generated by the wings, it is impossible for it to keep static in the air, that is, it must always be kept in motion. On the other hand, rotor aircraft can perform stationary flights since their propulsion system is directed vertically, likewise, they can achieve smooth maneuvers and they have the ability to perform rotational and lateral displacements. However, this type of aerial vehicles have several limiting aspects, such as the slow speed of movement and a greater energy consumption to perform this movements, it means, the aircraft must generate an inclination to produce certain quantity of longitudinal thrust or rotational motion. As expected, these two types of drones have very different applications, however, an UAV could obtain specific capabilities of these two, using the so-called convertible hybrid drone. Which allows to expand its possible applications such as: inspection of roads or power grids, for delivery systems in remote locations and with difficult access and for support or rescue missions. This can be done through a long-range flight and, if it is necessary, the UAV can change to hover flight mode either landing or to maintain a static position and supervise an static event.

UAV's have been improved for more than 100 years to have greater applications, so their flight control systems have been developed over the years to achieve excellent flight behavior. These flight controls are mainly based on in its structure, aerodynamics and its propulsion system, so each design has a different control system. At present, these control systems are well investigated, so the behavior of UAV's in the air is very stable and even, they have the capabilities of perform several tasks autonomously. Over the years different drones with hybrid flight capabilities have been designed in order to obtain the flight benefits of both types (fixed wing and rotor craft), but because they are relatively new systems, their flight control system basically consist of the combination of the controls of the two flight classes while their transition is based on the switching between the two controls. Most of the papers related with this topic tackle the problem from a simplified model without taking into account aerodynamics, bounded limits of actuators, or even continuity of the controller. In this work we have focused to develop and implement a control system dedicated especially to the transition maneuver from hover to cruise flight mode and vice-versa of a Tail-sitter drone. This approach not only considers aerodynamics effects, but also a real scenario in which usual available states in practice are only needed. The controller design relies in a simple control algorithm. We have taken care of designing a smooth controller avoiding switching dynamics between modes, having sweet and bounded controllers. These are very desired properties in practice implementations resulting in a full continuous closed-loop system.

In the next chapters it is presented state of the art of the problem, problem statement, modeling and control and simulations that demonstrate effectiveness of the obtained results. Also preliminary experiments are presented.

CHAPTER 1

State of the art

In the past years several hybrid flight mode aircraft have been designed which models can be divided into two principal groups as can be seen at fig.1.1. Next we describe the current art of the work of these hybrid drones [1].

1.1 Convertible aircraft

In [1] an in-depth investigation of the different types of hybrid UAV's is presented, which are explained below. As the name suggests, convertiplane aircraft have the main characteristic of modifying part of its structure and operation to change the flight mode, this group can be divided into four subgroups according to the modification or functionality of its structure. We explain them next.

[1] Throughout this document we refer to *hybrid* to UAVs which in its mechanical structure, have airplane and helicopter capabilities. We refer to them also as convertible drones.

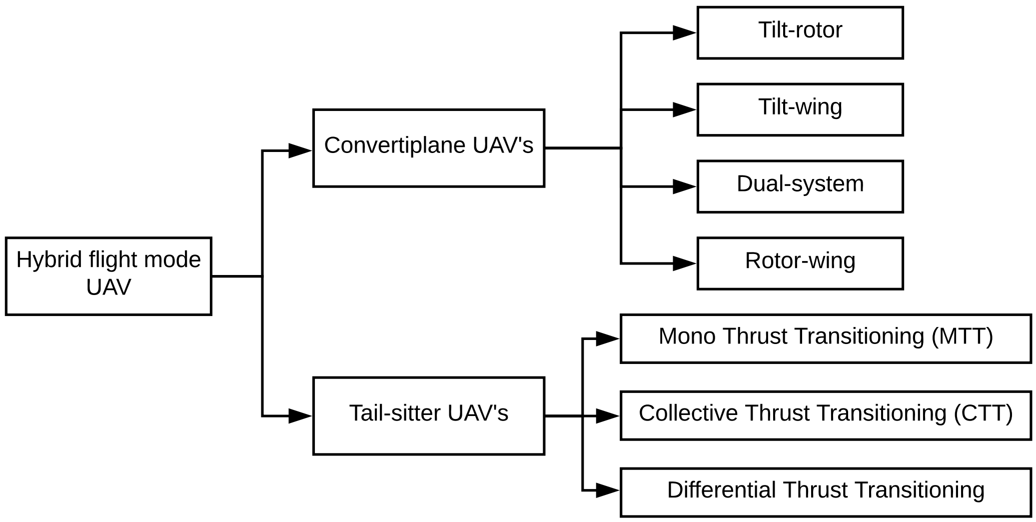


Figure 1.1: Hybrid UAV types diagram [1]

1.1.1 Tilt-rotor

This kind of UAVs have the property to tilt all or some of their motors to redirect the thrust force in such a way that they can generate both vertical and horizontal thrust.

The most emblematic models of this class of UAV are the Bell Eagle Eye, see fig. 1.2 (a), developed in 1993 by Bell Helicopter Textron Incorporation (BHTI) [2]. It was one of the first tilt-rotor drones which consists of two motors coupled by a rotary mechanism at the end of the wings and with a fuselage similar to a small plane.

Another interesting model is the Project zero [3], developed by AgustaWestland in 2013; this model has the peculiarity of having the propulsion motors located inside the wing area as it can be observed at fig.1.2 (b).

A different tilt-rotor model highly commercialized is the Navig8^{TM} UAV [4] shown at fig.1.2 (c), which has a structure similar to that of a helicopter. It has two thrust rotors, which are coupled in the side part of the main body. An important aspect of this UAV is that it can use fuel or electric energy source, according to its application.


(a) Bell Eagle Eye UAV


(b) The project zero UAV


(c) Navig8 UAV.


(d) upat


(e) IAI Panther

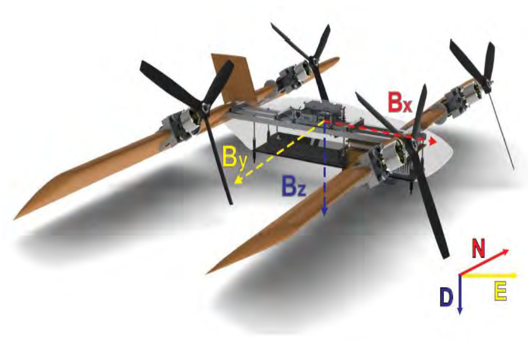

(f) TURAC

Figure 1.2: Tilt-rotor UAV models.

In the Bell Eagle Eye UAV, according to its structure the tilt rotor is made in different ways. Since the aircraft has a fixed wing, the rotors can be aligned completely horizontal because at the end of the transition from hover to cruise flight mode the wing can generate the necessary lift force to keep the aircraft flying. In the project zero UAV, the wing can not generate the sufficient lift force. Also, the navig8 UAV has a limited-surface-area wing, which results in a poor aerodynamic lift force. Others UAV of this subgroup are the NUAA UAV development [5] and the UPAT [6]. The last one has a bi-rotor structure. There are some designs which uses a tri-rotor frame, for instance we can cite to the Orange Hawk [7], IAI Panther [8], and the TURAC [9].

1.1.2 Tilt-wing

Tilt-rotor and tilt-wing UAVs are very similar, the only difference is that, in addition to tilting their motors, also the wings tilt as the names suggests. These models were developed since 1957 and some examples are the Unmanned Quad-TiltRotor shown at fig.1.3 (a). This model presented in [10] consists of a quad-rotor structure with wings aligned to the motors thrust direction. Its flight transition mode relies on tilting of their four motors and wings to obtain a horizontal thrust. Another interesting model is the Greased Lightning or GL-10 shown at 1.3(b) developed by NASA [11]. This aircraft consists of ten motors, eight of them distributed in front of the wings and aligned to them. The rest of their rotors are in the aircraft's tail same aligned to this. Similarly, the wings and tail have the ability to tilt to achieve the transition between flight modes.



(a) Unmanned Quad - TiltRotor [10]

(b) GL-10

(c) DHL parcelcopter

(d) AT-10 Responder

Figure 1.3: Tilt-rotor UAV models.

In these aircraft models the wing is tilted to change between flight modes. While in hover mode, the wing aircraft is positioned vertically, which can significantly change the aircraft aerodynamics having a non desirable effect produced by wind gusts. However, it is possible that this can not be a great impediment to the proper flying of this type of drones, due to improved flight control systems responsible to stabilize UAV position in all flying regimes. Even this type of models have been used by parcel companies to deliver products to less accessible places, such as camps in mountains or places far away where airstrips are not available [12].

1.1.3 Dual-system UAV

This kind of hybrid UAVs have two different thrust systems, one system for hover and other system for cruise flight mode. In other words it is like the combination of frame structure of both rotor-craft and fixed wing in only one aircraft. In these models the transition system relies in activating and deactivating one of the two thrust systems according to the actual flight mode. Some examples of dual hybrid UAV are the Arcturus JUMP 15 [13], shown at fig. 1.4 (a). This drone is developed by the company Arcturus UAV. It has a structure similar to that of a plane with a single front engine that has the function of generating the thrust while it is in cruise mode. In addition to that, this aircraft has an extra structure in each wing, parallel aligned to the fuselage, which have four more motors vertically aligned which are used for hover mode. Another interesting UAV within this subgroup is the HADA [5], shwon at fig. 1.4 (b) developed by the INTA (National Institute of Aerospace Technology) in Spain. Its functionality in hover is similar to an helicopter, since it has a single motor directed vertically, and two motors horizontally aligned; one motor is for the hover mode, like a helicopter, and the second motor aligned to the fuselage, is responsible to generate the horizontal thrust in cruise mode.

(a) Arcturus JUMP 15

(b) HADA

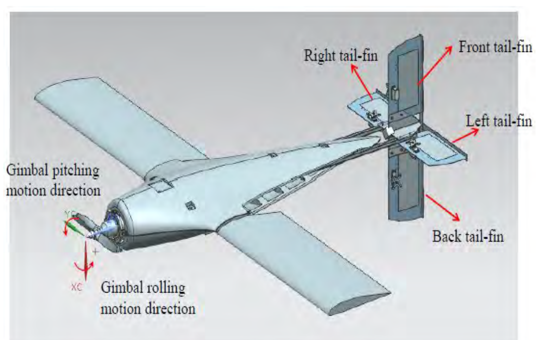
Figure 1.4: Dual-systems UAV models.

1.2 Tail-sitters

This group of hybrid drones, have the peculiarity of landing in the rear vertically oriented position, which implies that its structure does not change drastically. The transition is based on full tilting of the aircraft body, from approximately 0 degrees to 90. To carry out this transition there are different types of tail-sitters according to the way that the rotational forces are generated. This is shown in fig.1.1. In the following subsections we explain in detail each one of the types of tail-sitter that exist nowadays.

1.2.1 Mono Thrust Transitioning (MTT)

These hybrid models basically have a propeller motor attached either to the front or to the rear of the aircraft. This motor is used to generate propulsion in the two flight modes. For achieve the transition flight mode, the UAV uses either vectored-thrust, control vanes or cylinders that redirect the air generated by the motor. Some examples of these drones are the Hybrid UAV U-Lion [14, 15] shown at fig. 1.5 (a) which has a reconfigurable wing with a structure more similar to that of a fixed wing aircraft. It consists of two propulsion motors aligned in the same axis, this is the reason why it is considered as mono thrust UAV. Such motors rotate at different directions. During the hover flight mode the wings are folded and aligned to the fuselage and the motor thrust is directed vertically. While in the cruise mode, wings are placed perpendicularly to the fuselage obtaining the form of an airplane to start an inclination. The motors tilt a small angle with the help of a gimbal mechanism. Other models of this class of UAV are the Vertical Bat [16] shown at fig. 1.5 (c) which uses control vanes to achieve the transition between flight modes; the Flexrotor [17] shown at fig.1.5(b), and designed by AEROVEL. This last aircraft is created to perform terrestrial and maritime operations either day or night. The SkyTote [18] shown at fig.1.5(d) refers to a plane, but with a tail in the form of a cross, this is to be able to land in its tail.



(a) U-Lion

(b) Flexrotor

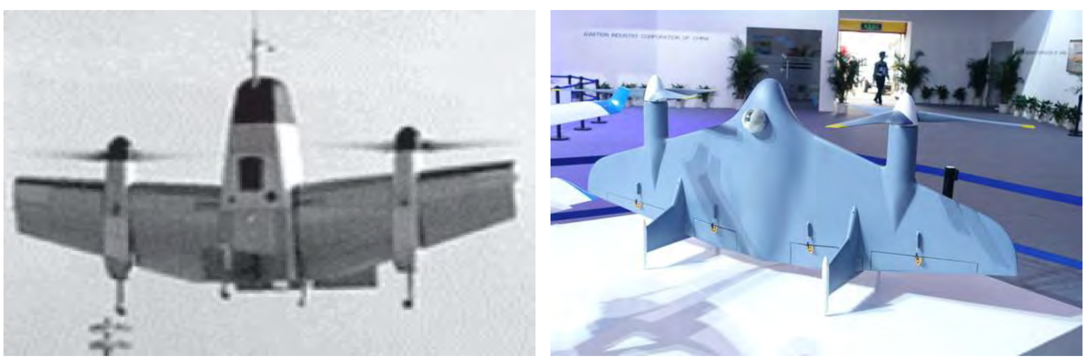
(c) V-Bat

(d) SkyTote

Figure 1.5: Mono Thrust Transitioning (MTT) UAV models.

1.2.2 Collective Thrust Transitioning (CTT)

Those classes of models are distinguished by having a pair of thrust motors and several control surfaces. The transition between flight modes is performed by the torque generated by surfaces changing UAV attitude. Very few models of this class of UAV have been developed and have shown good flight performances. Among such models are the T-wing [19] fig. 1.6 (a), developed by R.H. Stone at the University of Sydney in 2006. The T-wing uses elevons and rudders to achieve maneuvering within the two flight modes. Also, there is the VD200 [20] shown at fig. 1.6 (b) and developed by the Chengdu Aircraft Research and Design Institute (CARDI) in China 2016. This model has two thrust motors and four control surfaces. Elevons allow to perform all the maneuvers of both flight modes.



(a) T-wing

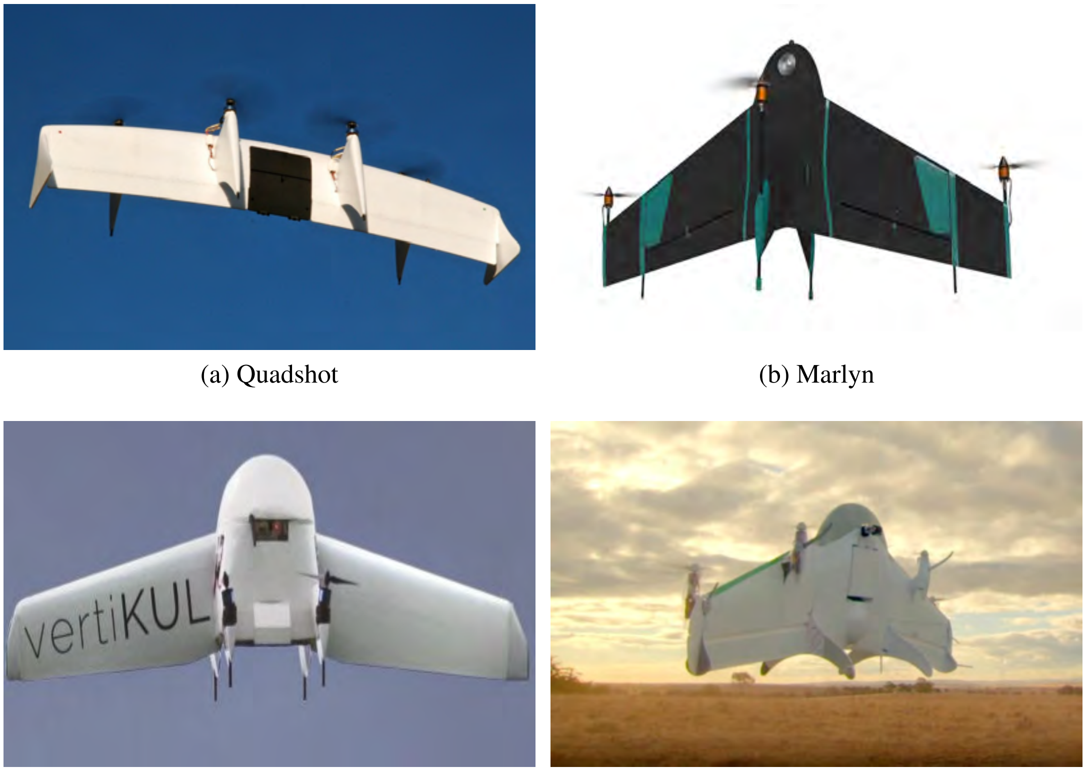
(b) VD200

Figure 1.6: Collective Thrust Transitioning (CTT) UAV models.

1.2.3 Differential Thrust Transitioning (DTT) UAVs

Finally, the DTT subgroup is characterized by containing more than two thrust motors aligned to the fuselage. Since this kind of models have more motors than the last model, it is possible that they do not require control surfaces to achieve the maneuvers in the transition phase. Such a transition is done through the force difference between thrusters of the different engines generating the torque needed to turn the aircraft to its vertical or horizontal position. Among the most common designs is the QuadShot presented in [21–23]. Quadshot is the simplest model w.r.t mechanical design, its composition consist only of a fixed-wing with four motors parallel to the plane formed by the wing. The QuadShot has two control surfaces to support the rotors to achieve the transition maneuver. Its structure is completely fixed, since it has not moving or rotating parts that modify its shape. A figure of this can be seen at fig. 1.7 (a). The Marlyn shown at fig.1.7 (b) is developed by ATMOS and is used specifically for photogrammetry [24, 25]. Unlike the Quadshot, this model has a ”+” motor arrangement, while the Quadshot has a ”V” shape in their motor configuration geometry. Another interesting model is the VertiKUL UAV [26], shown at fig.1.7 (c), which is also composed of four motors. In this case, those motors are aligned in an ”H” form. Another important difference in this model is that it does not have control surfaces, so all the maneuvers in both flight modes are performed by the thrust and torque difference in the motors. Finally, the Project Wing [27] developed by Google and shown at fig. 1.7(d), has a similar structure to the Quadshot, however it has a wider wing..

Summarizing the previous models, to this day there are a wide variety of hybrid UAV models which have different applications, operating modes, advantages and disadvantages, but at the end they perform both flight modes efficiently. But now, what is really important in this work is the process of change of flight mode which leads us to investigate within all these models described above. The next question arises: how to change automatically between flight modes? To answer this question, some factors must be taken into account for achieve a successful and safe transition.



(a) Quadshot (b) Marlyn

(c) VertiKUL (d) Project Wing

Figure 1.7: Differential Thrust Transitioning (DTT) UAV models.

1.3 Flight transition methods

According to the convertible UAV subgroups, different methods have been developed to perform the transition. For Tilt-rotor and Tilt-wing the methods are very similar. For instance in [10, 28] the control strategy consists in rotating the motor angles according to a predefined value until they are completely aligned to its desired value, after that, a switching strategy between flight modes is performed.

For tail-sitter's some transition control have been proposed. In [29], authors model and develop a robust control system to control the two flight modes that include a complete modeling of flight and prop wash dynamics. Also, such approach take into consideration the wing aerodynamics and most of the external facts that could affect the aircraft dynamics. The negative point of [29], is that they not get focus in the transition control, making a simple switching between the two flight modes, while the aircraft is increasing or decreasing its attitude angle. In [30], the transition is performed manually an the control algorithm relies in modifying the flight control modes weights according to the percentage of the transition progress. In [31, 32], it is implemented a controller in $SO(3)$ (special orthogonal group of dimension three) for the transition maneuver of a tail-sitter UAV. This consists in giving a reference angle until the pitch angle reaches the final desired value. The controller is designed in the 6-DOF, however the research lacks of a formal proof, which must demonstrate the effectiveness of their result. In [33] a design and implementation work of a quite robust control system is presented, considering factors such as aerodynamics, disturbances due to air gusts among other factors that are presented in a real environment. All this with the use of wind tunnels to acquire such information and optimizing the proposed control. Another important aspect in this work is that the control is continuous and is based on the current states that the system presents, thus giving a continuous behavior. However the papers lacks of a formal mathematical proof of the control algorithm. In [34] the control system is based on the tracking of desired values for the drone velocity movement by applying a PID control. For that aim, the desired speed increases or decreases according to the angle of the UAV in its vertical or horizontal positions.

In [14] a control system for the transition of the U-Lion is presented. It consists of a Proportional-Derivative control, and same as in [34] the change of inclination is based on a constant rotation in the UAV desired attitude angle. In such a work the author chooses to use Euler angles in conjunction with rotational matrices in order to eliminate the singularity that occurs in the Euler angle system. On the other hand, in [23,35] the control system during the transition has very defined conditions which the UAV must maintain, in this case, the author define a minimum speed which the UAV should reach to make the change of flight control, as well as maintain a constant angular velocity to achieve the desired attitude. To explain in detail the transition process, suppose that the UAV is flying in the hover mode, once the pilot gives the signal by radio to the drone to do a flight mode transition, the controller generates a desired signal for the angle of inclination in the pitch in such a way that this angle will decrease linearly from approximately 90 to 40 degrees doing the UAV tilts a thrust difference of each pair of motors. Once the drone has reached the desired final angle, this signal for the tilt angle will instantly change to zero since at that time the control of the flight mode will also have changed to cruise control. Knowing this, it is clear that the control for the transition is not continuous. On the other hand, since said system focused on the UAV inclination, the height and speeds were not really taken into account that they only determined a minimum speed that the drone should meet during the transition. Finally, to make the change between flight modes and controls, the UAV must achieve two conditions of speed and angle. Another important work that is very useful for the study of the transitions of flight modes is presented in [36], in which the effect of wing on tail-sitter models is studied. This research tries to determine the forces that could be generated due to the wing gust by the UAV velocity, air speed in the environment and the air currents that are generated by the propellers. These studies can be a great contribution to determine with better accuracy the system aerodynamics. With respect to the aforementioned transition control methods, in [37] the authors implement a unified control system with the ability to handle the three flight modes (hover, transition and level flight) composed of two closed loop control systems (attitude and position) applied to a quad-rotor tail-sitter, they model the system with the characteristics of a fixed-wing aircraft, that is, taking into account the lifting and dragging forces generated by the wing-wind interaction.

CHAPTER 2

Problem formulation

Although there is currently a wide variety of hybrid drone models and several approaches for its corresponding flight control systems, the development of these aircraft has led to the expansion of a large number of applications that the UAV can now perform in a very safe and effective way. But there is a very important factor that even now has not been studied or analyzed in a deep way, since its relevance has not been taken in the size it should be, that is, the *transition between flight modes*. This process that is carried out during the change of flight of the UAV between the hover mode to the cruise mode (and vice versa) until now has only been studied in very few papers. In those works usually the change between flight modes is performed simply as a *switching* between two control algorithms. In other words, if UAV is currently flying in cruise mode, when a change of flight is required, the UAV changes from horizontal to vertical attitude using the proposed control algorithm. Once the UAV reaches a threshold or limit angle determining now a hover flight status, the control algorithm changes directly to hover mode. These systems of flight change appear normally in tilt-rotor, tilt-wing and in most of the tail-sitter UAV's. On the other hand, there are flight change algorithms that focus on changing the flight control system gradually, depending on the percentage of the drone's attitude change, this method is presented more clearly in a dual-system UAV, since it has two system of independent propulsion (for hover and for cruise), while the hover is being active, the flight control has a 100% weight in the total control and, if the change to the cruise mode is required, it begins to use horizontal propulsion. In this way, When a certain percentage of weight is reached in the control in cruise mode, (70% hover and 30% cruise, for example) and once it reaches a threshold speed or angle, the control weight goes completely to the current flight mode.

If we look closely at these systems of flight change, it is easy to determine that their control logic is based only on previously defined speeds and attitude regardless of current state values, which implies that the UAV will only attempt to reach a desired state without having a continuous feedback of its current status. Clearly these control systems do not determine a really stable result, thus giving a great possibility of failure when facing unsuitable or not very controlled conditions. For this reason, the work carried out in this document aims to study in a more profound way the behavior of a hybrid UAV during the transition with a tail-sitter model of collaborative thrust in order to propose, develop and implement a new control system fully focused in the transition between the two flight modes. This system aims to take into account the aircraft aerodynamic forces as well as the forces generated by the different propulsion motors. Since the model used in this work has air control surfaces, such as ailerons, it is also intended to take into account such mechanisms for the generation of a mathematical model as complete as possible. Also, the controller must be as simple as possible, but also functional and robust, to be embedded in a micro-controller.

Fig.2.1 depicts the tail-sitter drone used in this study, this UAV have three modes of operation: a) hover; b) cruise; and c) transition. The last mode consists in the change phase between cruise (hover) to hover (cruise); **this flying mode will be investigated in this document**. To define more clearly what the transition between the flight modes consists of, we will assume that the UAV is flying at a stable height in the hover flight mode [1]. This implies that both its position and its attitude are practically constant, that is, a constant orientation of 90 degrees with respect to the *N* axis of the North, East, Down (NED) coordinate system. Once the transition stage starts, the UAV will have to change its orientation to approximately 0 degrees, performing the coordinate system of the body be aligned with the NED coordinate system. Once UAV has reached that orientation and its displacement is now on the *N* axis, the transition from hover to cruise has been completed. It is important to mention that this tilting should not be made as fast as possible, since for a fixed-wing type aircraft to be able to stay in the air, it must reach a minimum speed that generates enough lift force according to its wing profile.

Now, in order to change the flight mode from cruise to hover, the reverse process of the aforementioned above must be carried out. In fig.2.2 it is shown a diagram which explain generally the transitions between flight modes.

As mentioned above, in this work the Quadshot model will be used, since it is the simplest UAV with simple handling structure, as well as the energy consumption is minimal because it does not have dedicated motors for each flight mode. This UAV has six actuators in total: four rotors and two servos which manipulate the pitch and roll angle. It is important to mention that the presence of these six actuators results in an over-actuated roll and pitch subsystems, so, sometimes groups of actuators are taken to represent a single acting force. In fig.2.3 a general diagram is presented showing the execution flow of the different control algorithms (hover, cruise, transition) according to the current UAV status.

[1] This assumption is easy to follow, since hover controllers for Tail-sitters UAVs are well investigated in the literature. In fact, the proposed controller cab be used in hover mode with some minor modifications

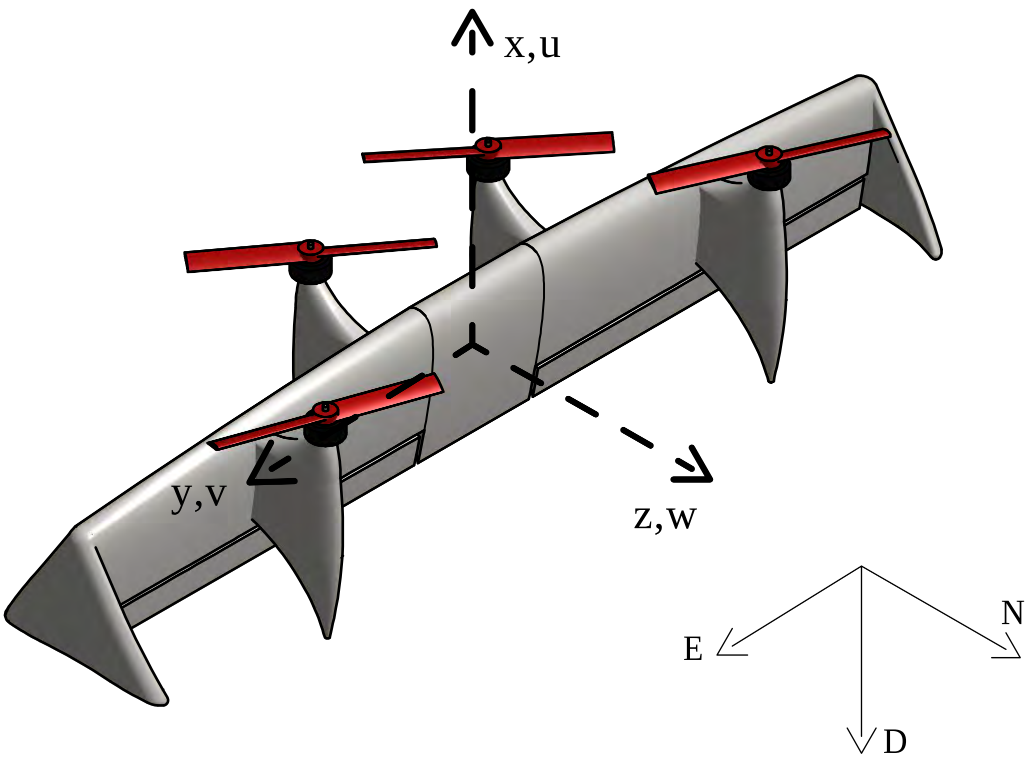


Figure 2.1: Aircraft reference frames used in this document.

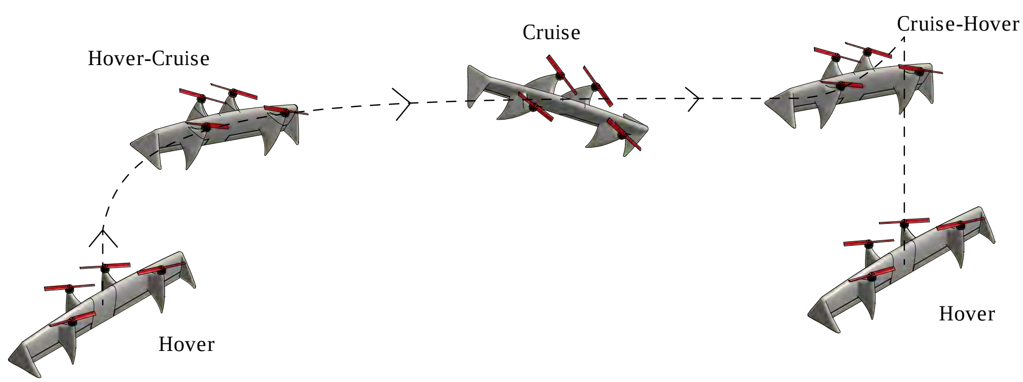


Figure 2.2: Change between flight modes. Description of hover-cruise and cruise-hover.

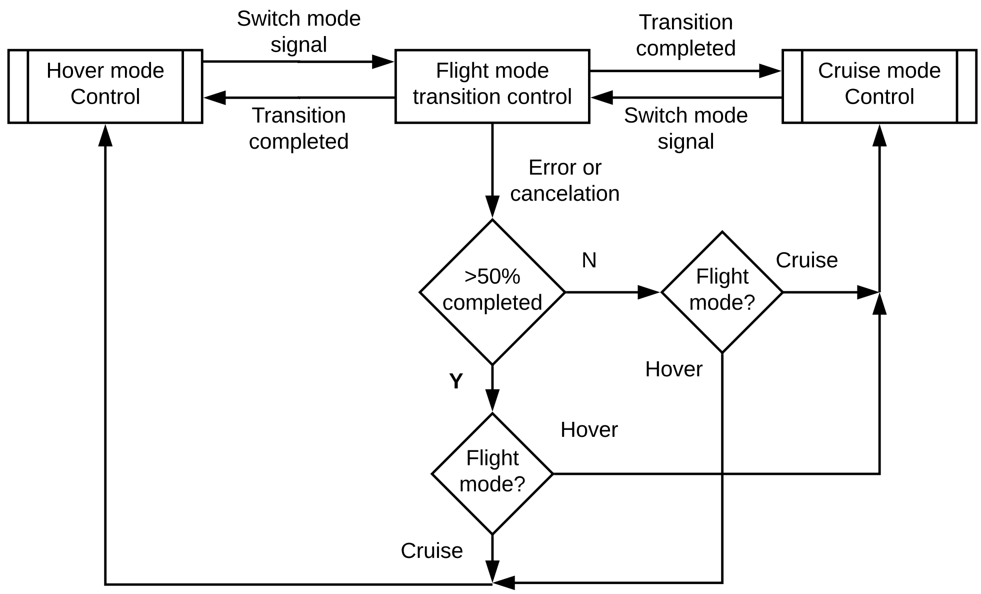


Figure 2.3: Flow digram of the aircraft full control system.

2.1 System model

The analysis and control design is implemented on the (N,D) plane, i.e. the inertial frame, and (x,z) from the body frame. The reason why this plane is only taken into consideration is because the movement required for the transition maneuver lies in the rotation of the aircraft only on the y-axis of the body. This way, the forces or dynamics acting on the UAV will be only analyzed in this coordinate plane. Another very important aspect to take into account is that the dynamics of the system will be analyzed within the body framework. This is due to the forces act in reference to the direction and orientation of the body [38], [39] [2]. And by consequence, we avoid unnecessary complexity by avoiding to perform a system rotation during the calculation or execution of the algorithm. The forces that affect the behavior of the aircraft are

[2]Nonetheless, the coordinates can change from body to inertial frame by simply multiplying the system by the corresponding rotation matrix.

shown in fig.2.4.

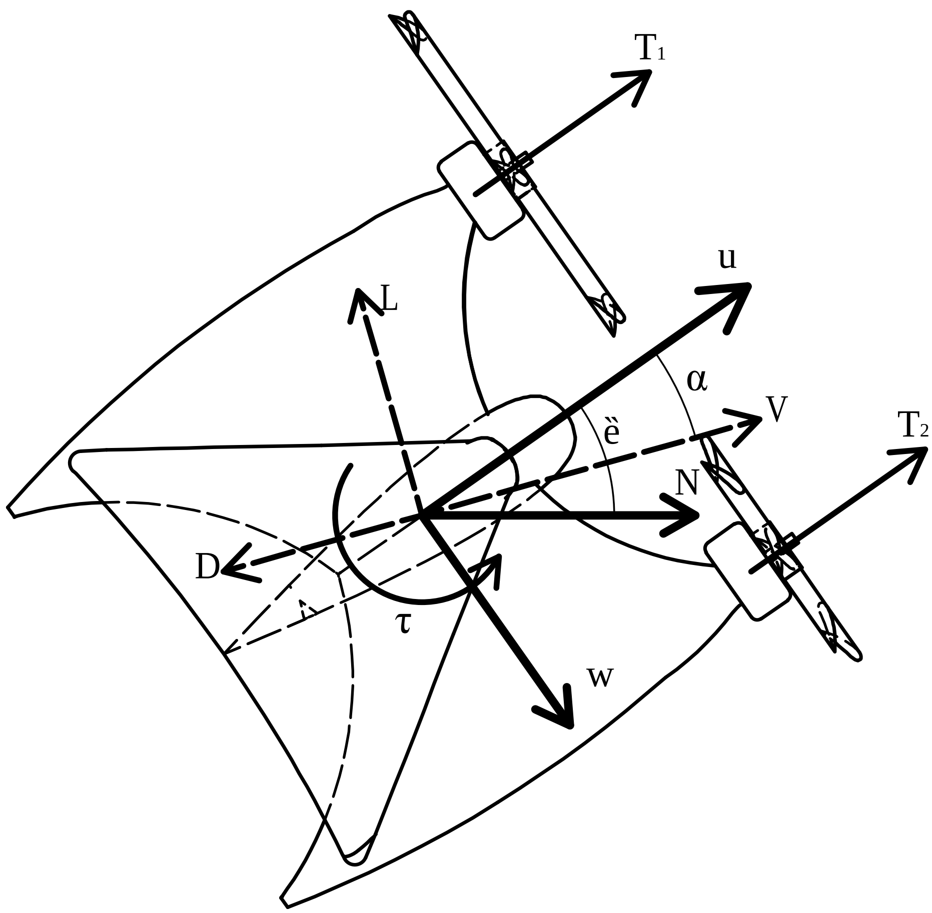


Figure 2.4: Main system variables presented in the longitudinal dynamics of the tails-sitter UAV used in this work.

According with the frames shown at fig.2.4, the system can be described as follows

$$\Sigma_1 \quad \begin{cases} \dot{u} = -D\cos\alpha + L\sin\alpha + T - g\sin\theta - qw \\ \dot{w} = -D\sin\alpha - L\cos\alpha + g\cos\theta + qu \end{cases} \tag{2.1}$$

$$\Sigma_2 \quad \begin{cases} \dot{\theta} = q \\ \dot{q} = \tau, \end{cases} \tag{2.2}$$

since the attitude subsystem Σ_2 is fully independent of the translational dynamics, but the translational dynamics does not, the system can be divided into two separated subsystems where Σ_2 is the orientation and Σ_1 is the translation dynamics. The u and w states are the horizontal and the vertical velocities respectively, w.r.t. the body frame. In this case, it is preferable to know the UAV velocity of displacement. The variable θ is the y-axis angle of rotation; q is the corresponding angular velocity between the inertial and the body frame; D, L and g are the drag, lift and gravity forces respectively; α is the angle of attack (AoA) that depends of the air velocity vector and the body velocities where

$$\alpha = \tan^{-1}\frac{w}{u}, \tag{2.3}$$

finally T and τ are the two control inputs that will modify the accelerations and rotations of the whole system.

In systems (2.1) and (2.2) it can be seen that subsystem Σ_2 has a faster dynamics than subsystem Σ_1, [16]. Thus, the attitude angle should not be controlled as fast as it can because it could cause instability in the translational state as a result of the orientation dependence in Σ_1. In this way, it is crucial to do a time scale separation [40,41] that help to determine how the subsystem Σ_2 should be controlled allowing the states evolution of each subsystem be similar and converge to a desired time at least asymptotically in time.

If in any case it is necessary to obtain information in the referential framework, either to perform position or orientation calculations, or in the same way to transform trajectories that have been generated from the inertial frame. The rotation matrix that describes the translation from the NED (North, East, Down) coordinate frame to the body frame is defined as

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix}, \tag{2.4}$$

For simplicity the controller is designed on the body frame, avoiding extra terms from the aforementioned rotation matrix.

2.2 Aerodynamic forces

The proposed model considers aerodynamic terms explained next. The *lift* and *drag* forces are functions of several variables, but the most important of these variables are: the air speed and the lift and drag coefficients. Lift and drag are defined as follows

$$\begin{aligned} L &= K_1 C_L V^2 \\ D &= K_1 C_D V^2 \end{aligned}$$

where $V = \sqrt{u^2 + w^2}$ is the air speed magnitude [42]. The drag and lift coefficients (C_L, C_D) for the airfoil used in this experiment are described at fig. 2.5 according to the angle of attack (AoA) α. Such coefficients correspond to a symmetrical airfoil NACA-0020 shown at fig. 2.6, this airfoil is used in the real platform. The data corresponidng to those variables were obtained by numerical simulations made in the software XFR5 with many different Reynold numbers. Also it was designed some different airfoils that include aileron angles (β) to obtain different lift and drag coefficients which will help the aircraft to produce lift and also produce a part of the torque needed to rotate. Finally, K_1 defined as $K_1 = \frac{\rho S}{2}$, describes the wing hitting area (S). Air pressure is defined by ρ. Those variables affect the complete amount of lift or drag force.

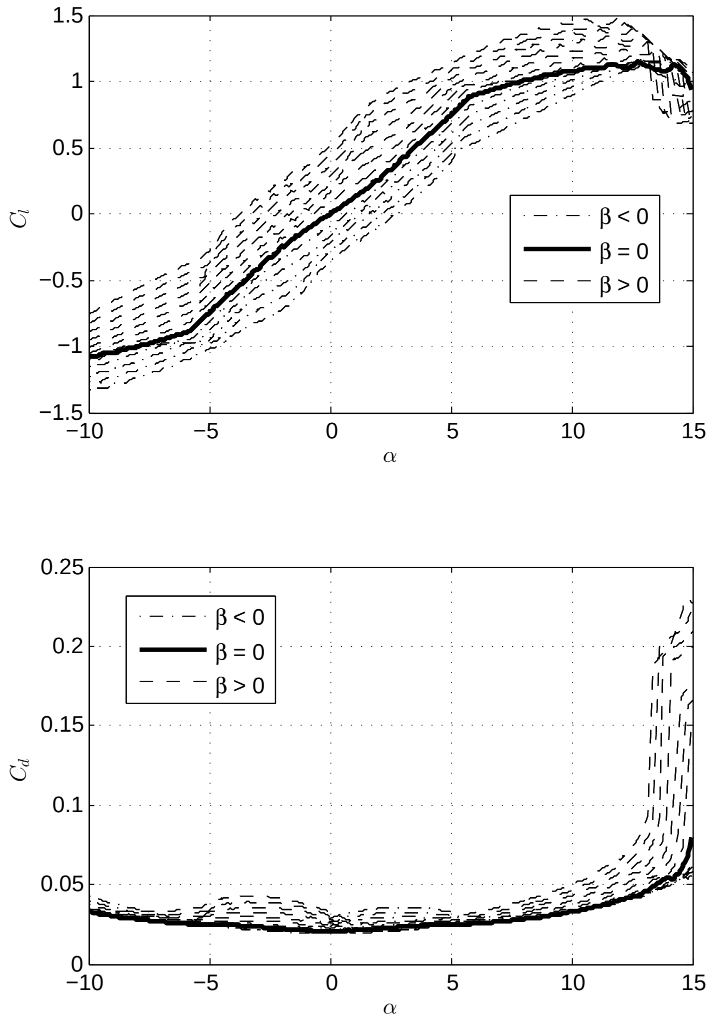


Figure 2.5: Lift and drag coefficients w.r.t α angle obtained from XFR5 software and [43], where $\alpha = 12$ degrees corresponds to the best AoA according to the relation between the C_L and the C_D.

The control inputs for the system (2.1-2.2) are the thrust T and the torque generated by the difference of thrust between rear and from rotors and from the aileron movement

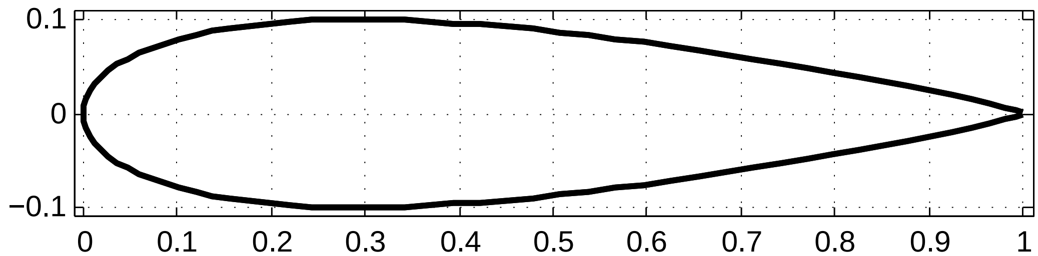


Figure 2.6: Airfoil normalized profile used in the aircraft (NACA-0020).

τ. These terms can be modeled as

$$T = T_1 + T_2 \tag{2.5}$$

$$\tau = \tau_\beta + \tau_{L(u,w)} + (T_1 - T_2) \tag{2.6}$$

where τ_β is the part of torque generated by the propellers wind stream in the aileron; $\tau_{L(u,w)}$ is the torque induced by wind stream shocking in the wing area; and the rest of the torque is originated by the difference force between the front and back pair of motors. The total thrust force is calculated by the sum of each motor thrust of the aircraft.

We are ready to state the following problem statement.

2.3 Problem Statement

Design a control algorithm that let a hybrid flight mode aircraft represented by system (2.1, 2.2) to change securely from hover to cruise flight mode, and vice versa, through the difference of thrust of its motors and with the help of its ailerons. That control should be continuous, stable at least asymptotically in time, with low computational hardware requirements and easy to implement.

CHAPTER 3

Main Result

In this section it is presented the control design technique that was carried out to develop the control algorithm which will carry the aircraft to achieve an stable and safe flight mode transition. Finally, the mathematical proof is presented in order to demonstrate the stability of the closed-loop system. The controller design and the closed-loop stability proof is carried out by using the Lyapunov stability theory [37, 44].

3.1 Control design technique

The key idea behind the proposed controller is explained next. Based on time-scale separation principle presented in the UAV's previously demonstrated in [20, 40, 41], it is possible to use the variable θ as a virtual controller for subsystem (2.1). Once this virtual controller is designed, its value must be tracked by the subsystem (2.2). Such subsystem is enough faster than (2.1), then it is possible to control the complete system by this approach. In other words, since the dynamics of translation depend on the dynamics of θ and because their speed is equally affected by the different components of $Lift$ and $Drag$ it is not recommended that the state $theta$ be controlled as fast as possible since it can cause $\sum_1$ to be of some unstable nature. Therefore, if a time scale or a certain delay were applied in $theta$ dynamics, it could be achieved in such a way that both sub-systems to converge in a similar time, thus ensuring stability in the whole system.

Let's start with the design of the virtual controller for (2.1). In this case states u and w should converge to a predefined values according to the appropriate characteristics for the flight mode in question. Said that, subsystem (2.1) can be rewritten as

$$\dot{u} = f_1(u,w) + T - \sqrt[2]{1-\varepsilon^2} \tag{3.1}$$

$$\dot{w} = f_2(u,w) + \varepsilon \tag{3.2}$$

where

$$\begin{aligned} \varepsilon &= \cos\theta \\ f_1(u,w) &= -D\cos\alpha + L\sin\alpha \\ f_2(u,w) &= -D\sin\alpha - L\cos\alpha, \end{aligned}$$

Now, before proposing the control algorithm we should define some assumptions that we will take into consideration for the controller design. Such assumptions are:

Assumption 1. *In cruise flight mode (aka airplane mode) it is natural to consider that* $u >> w$ *holds, i.e. the horizontal velocity is much greater than vertical velocity in the body frame.*

Assumption 2. *In hover mode,* $u \approx 0$ *and* $w \approx 0$*, since there is no displacement in horizontal and vertical directions. When such values arise, it means that a hover position* *is achieved.*

Remark 1. *Since* $\alpha = \tan^{-1}\frac{w}{u}$ *holds, the state u must never be equal to zero.*

Remark 2. *T, by nature, can not be negative, and in fact T is limited by the motor thrust capacity.*

Remark 3. *Since* (3.1) *holds, therefore* $0 \leq \varepsilon \leq 1$.

Remark 4. θ *is chosen to be bounded from* -10 *to* 100 *degrees to ensure a secure transition maneuver; these limits are chosen by the control designer.*

It is fundamental that u_d and w_d have to be defined according to the speed characteristics of each flight mode. As it is known, if the flight transition maneuver is from hover to cruise mode, u should increase to a value in which the lift force is sufficient to maintain the aircraft at a constant altitude. On the other hand, w must be designed w.r.t. u in such a way that the aircraft angle of attack (AoA) be the most effective angle for flying, in this case for the chosen airfoil is $\alpha \approx 6$ degrees. In the same way, when the transition is from cruise to hover, both speeds must be reduced in such a way that the AoA decreases to the point of being equal to zero. Knowing this, a correlation could be made between these two variables (u, w) to obtain the graphs of the desired speeds, i.e. (u_d, w_d).

Once the virtual control input ε replaces θ from (2.1), it is time to design a control system for (3.1) and (3.2) according to the new inputs. In this case T is maintained from the original system, and now ε that was created will help to momentarily replace the orientation state. As can be seen in (3.1), the virtual control variable is limited to $0 \leq \varepsilon \leq 1$, so the control will be saturated, which consists of applying chained linear saturation functions in order to maintain the saturation property, i.e., a control within the range of desired values. The used saturation function is defined in [45] as $\sigma(s)$ as a continuous non decreasing function satisfying

a) $s\sigma(s) > 0 \qquad \forall s \neq 0$

b) $\mid \sigma(s) \mid \leq M \qquad \forall s \in \mathbb{R}$

c) $\sigma(s) = s$ when $\mid s \mid \leq L$.

Remark 5. *The saturation property is designed in all controlled mechanical systems, since theoretically it is possible to obtain a non saturated control which leads to instability, malfunctioning and failure in the system. We avoid that by proposing a saturated controller.*

Once we have defined the control characteristics, it is now possible to propose a control algorithm given by

$$\varepsilon = -\sigma_2\big(f_2(u,w) + \sigma_1(w - w_d) - \dot{w}_d\big) \tag{3.3}$$

$$T = -\sigma_3(u - u_d) + \sqrt[2]{1 - \varepsilon^2} - f_1(u,w) + \dot{u}_d, \tag{3.4}$$

3.2 Proposed control system

Theorem 1. *Let system dynamics (3.1) and (3.2) where $u \neq 0$. Applying the controllers (3.3) and (3.4) to the aforementioned system, with $\sigma_i(\cdot)$ be differentiable linear saturation function for given $L_i, M_i \in \mathbb{R}_+$ values and $L_i < M_i \quad \forall i = 1,2,3$ where $M_1 < \frac{L_2}{2}$ and such that $M_2 \leq 1$, also be u_d and w_d continuous desired functions with $u >> w$, then, for any initial conditions $u(0), w(0)$ with exception of $u(0) = 0$ with $u, w \in \mathbb{R}$, the system will converge to the desired u_d and w_d values asymptotically.*

Proof. Define a variable change where

$$
\begin{aligned}
x_1 &= u - u_d \\
\dot{x}_1 &= \dot{u} - \dot{u}_d \\
x_2 &= w - w_d \\
\dot{x}_2 &= \dot{w} - \dot{w}_d
\end{aligned}
$$

and applying it in system (3.1), (3.2), this will take the form

$$
\dot{x}_1 = f_1(x_1 + u_d, x_2 + w_d) + T - \sqrt[2]{1 - \varepsilon^2} - \dot{u}_d \tag{3.5}
$$

$$
\dot{x}_2 = f_2(x_1 + u_d, x_2 + w_d) + \varepsilon - \dot{w}_d \tag{3.6}
$$

substituting the controls (3.3) and (3.4), the closed-loop system results in

$$
\dot{x}_1 = -\sigma(x_1) \tag{3.7}
$$

$$
\dot{x}_2 = f_2(x_1 + u_d, x_2 + w_d) - \sigma_2\big(f_2(x_1 + u_d, x_2 + w_d) + \sigma_1(x_2) - \dot{w}_d\big) - \dot{w}_d \tag{3.8}
$$

then, proposing a candidate Lyapunov function as

$$
V(\mathbf{x}) = \frac{1}{2}x_1^2 + \frac{1}{2}x_2^2, \tag{3.9}
$$

where

$$
\dot{V}(\mathbf{x}) = x_1\dot{x}_1 + x_2\dot{x}_2
$$

This function was chosen because it is positive defined and has the property of tending to infinity, when the variable t also tends to infinity, so if it is possible to find stability in the system, it can be assured that the system is GAS.

So substituting

$$\dot{V}(\mathbf{x}) = \quad -x_1\sigma(x_1) + x_2 f_2(x_1 + u_d, x_2 + w_d)$$
$$-x_2\sigma_2\big(f_2(x_1 + u_d, x_2 + w_d) + \sigma_1(x_2) - \dot{w}_d\big) - x_2\dot{w}_d$$

where $-x_1\sigma(x_1)$ is always negative because of property (a) of $\sigma(\cdot)$. The second term $x_2 f_2(x_1 + u_d, x_2 + w_d)$ is also negative since the sign of $x_2 f_2(\cdot,\cdot)$ is opposite of the sign of x_2, and assuming that $\dot{w}_d \approx 0$ the last argument approximates to zero, so $\dot{V}(x_1, x_2) < 0$ $\forall f_2(\cdot,\cdot) \notin Q_{f_2}$ where $Q_{f_2} = \{f_2(\cdot,\cdot) :| f_2(\cdot,\cdot) | \leq \frac{1}{2}L\}$ and $\sigma_1(x_2) < \frac{1}{2}L$. So that x_1 and x_2 enters in a finite time to the linear part of the saturation function [46] demonstrating local stability. Now due to the invariance characteristic of the previous sets, the states stay on the linear part letting the system be in a finite time

$$\dot{x}_1 = -x_1 \tag{3.10}$$

$$\dot{x}_2 = -x_2 \tag{3.11}$$

where such a subsystem is globally asymptotically stable. □

Once the virtual control ε was designed and several simulations were carried out, it was possible to obtain the evolution of the control ε while the velocities u and w converges to the desired values.The variable ε was used to replace the state θ of the complete system so that, in this way, a continuous function can be defined for the desired value for θ in such a way that it is now possible to design a control for the attitude dynamics according to the translation dynamics. Now, going back to the original system defined as

$$\begin{aligned}\dot{u} &= f_1(u,w) + T - g\sin\theta - qw &(3.12)\\ \dot{w} &= f_2(u,w) + g\cos\theta + qu &(3.13)\\ \dot{\theta} &= q &(3.14)\\ \dot{q} &= \tau &(3.15)\end{aligned}$$

now it is possible to define the second control input τ which will modify the attitude dynamics in order to finally make the transition change of the aircraft. This control as can be seen, it is easier to define since the dynamics of this subsystem has been considered only with the control input, therefore, τ control is proposed as

$$\tau = -k_\theta(\theta - \theta_d) - k_q(q - q_d) \tag{3.16}$$

and

$$T = -\sigma(u - u_d) + g\sin\theta - f_1(u,w) + \dot{u}_d. \tag{3.17}$$

with this, the attitude subsystem can follow a safe trajectory such that it does not cause instability or undesirable behavior in the translation subsystem since it has the characteristic of being a slower system as mentioned above. As it can be seen, these two controllers are not controlling directly the state w, but because of defining a θ_d and a u_d, it can be ensure an stable w state behavior.

Theorem 2. *Being the system dynamics (3.12)-(3.15) where $u \neq 0$. And applying the control inputs (2.6) and (3.4), where $\sigma(\cdot)$ is a linear saturation function for given L, M positive values such that $L < M$, with u_d and θ_d continuous differentiable functions as the desired state values. Then, for a set of initial conditions u, w according to the actual system restrictions, the system will converge to the desired values in a finite time.*

Proof. Applying a coordinate change over the original system with

$$\begin{aligned} x_1 &= u - u_d \\ \dot{x}_1 &= \dot{u} - \dot{u}_d \\ x_2 &= w - w_d \\ \dot{x}_2 &= \dot{w} - \dot{w}_d \\ x_3 &= \theta - \theta_d \\ x_4 &= \dot{x}_3 = q - q_d \end{aligned}$$

the new system has the form

$$\begin{aligned} \dot{x}_1 &= f_1(x_1 + u_d, x_2 + w_d) + T - g\sin(x_3 + \theta_d) - (x_4 + q_d)(x_2 + w_d) - \dot{u}_d \\ \dot{x}_2 &= f_2(x_1 + u_d, x_2 + w_d) + g\cos(x_3 + \theta_d) + (x_4 + q_d)(x_1 + u_d) - \dot{w}_d \\ \dot{x}_3 &= x_4 \\ \dot{x}_4 &= \tau \end{aligned}$$

and substituting the controls it follows that

$$\dot{x}_1 = -\sigma(x_1) - (x_4 + q_d)(x_2 + w_d) \tag{3.18}$$

$$\dot{x}_2 = f_2(x_1 + u_d, x_2 + w_d) + g\cos(x_3 + \theta_d) + (x_4 + q_d)(x_1 + u_d) - \dot{w}_d \tag{3.19}$$

$$\dot{x}_3 = x_4 \tag{3.20}$$

$$\dot{x}_4 = -k_\theta(x_3) - k_q(x_4) \tag{3.21}$$

in this case the x_3 and x_4 states are independent of x_1 and x_2 states. Also, as the structure of that subsystem is globally asymptotically stable (GAS), then it will be analyzed the stability of the two first states, proposing the Lyapunov's candidate function

$$V(\mathbf{x}) = \frac{1}{2}x_1^2 + \frac{1}{2}x_2^2, \tag{3.22}$$

where

$$\dot{V}(\mathbf{x}) = x_1\dot{x}_1 + x_2\dot{x}_2$$

after applying the substitution it obtains

$$\dot{V}(\mathbf{x}) = -x_1\sigma(x_1) + x_2(f_2(x_1+u_d, x_2+w_d) + g\cos(\theta_d) - \dot{w}_d),$$

as the states x_3 and x_4 where demonstrated to be GAS, it is possible to suppose that they will be converge to zero in a finite time, so this states and q_d(angular speed) values can be expected to be zero. Now, as the definition of σ, the argument $x_1\sigma(x_1)$ is always positive $\forall x \neq 0$. And as a property of $f_2(\cdot,\cdot)$, where the sign of the function is the counter of the input argument x_2 and assuming that $\dot{w}_d \approx 0$, because of θ_d is known, it can be supposed that $g\cos\theta_d$ is always positive, so, for ensure stability in x_2, $| f_2(\cdot,\cdot) | > g\cos\theta_d$. Demonstrating local asymptotically stability. □

CHAPTER 4

Simulation Experiments

In this Section MATLAB simulations were performed, where two experiments are conducted: transition from hover to cruise mode and vice-versa. The results are explained next.

4.1 Hover to cruise flight mode

As said before, during hovering, the initial conditions before the transition considers that (u,w) are approximated equal to zero and $\theta = 90$ degrees. Applying this to the simulation, the results are shown in fig. 4.1 where θ, α and τ control evolution over time from hover mode to cruise mode, which is set at 12 degrees approximately. The fig. 4.2 depicts the thrust control as the u and w evolve over time. According to the conditions established for the hover mode, at he end of the transition it is achieved when $u >> w$, this is due to the conditions of cruise flight mode. As it can be seen in graphs,

θ_d is a decreasing function with a smooth change relation from the mentioned above. As we have discussed in previous section, the translation speed system dynamics are slower than the attitude dynamics.

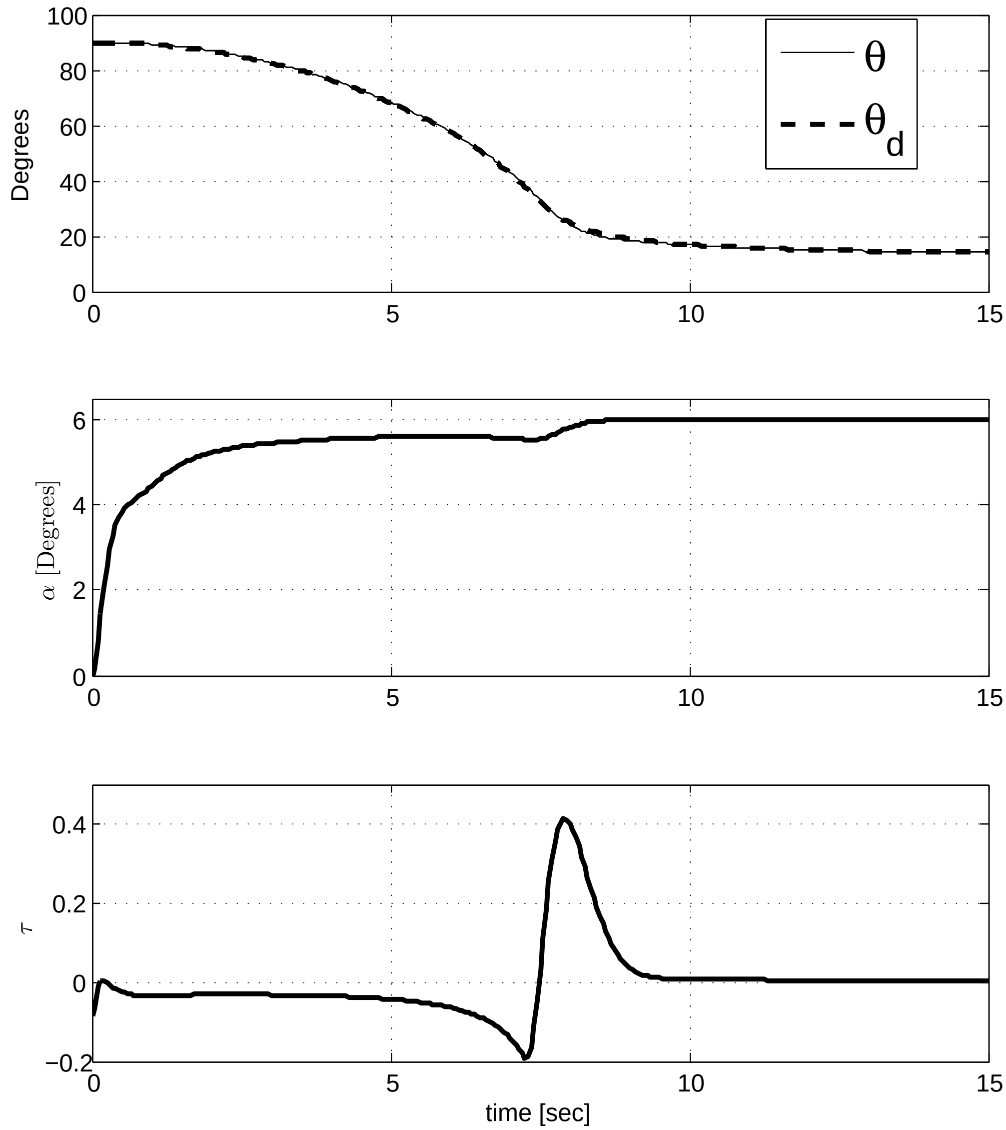


Figure 4.1: Closed-loop system: Hover to cruise mode simulation. Variables θ and α evolution according to the θ_d signal, also this figure presents the control τ.

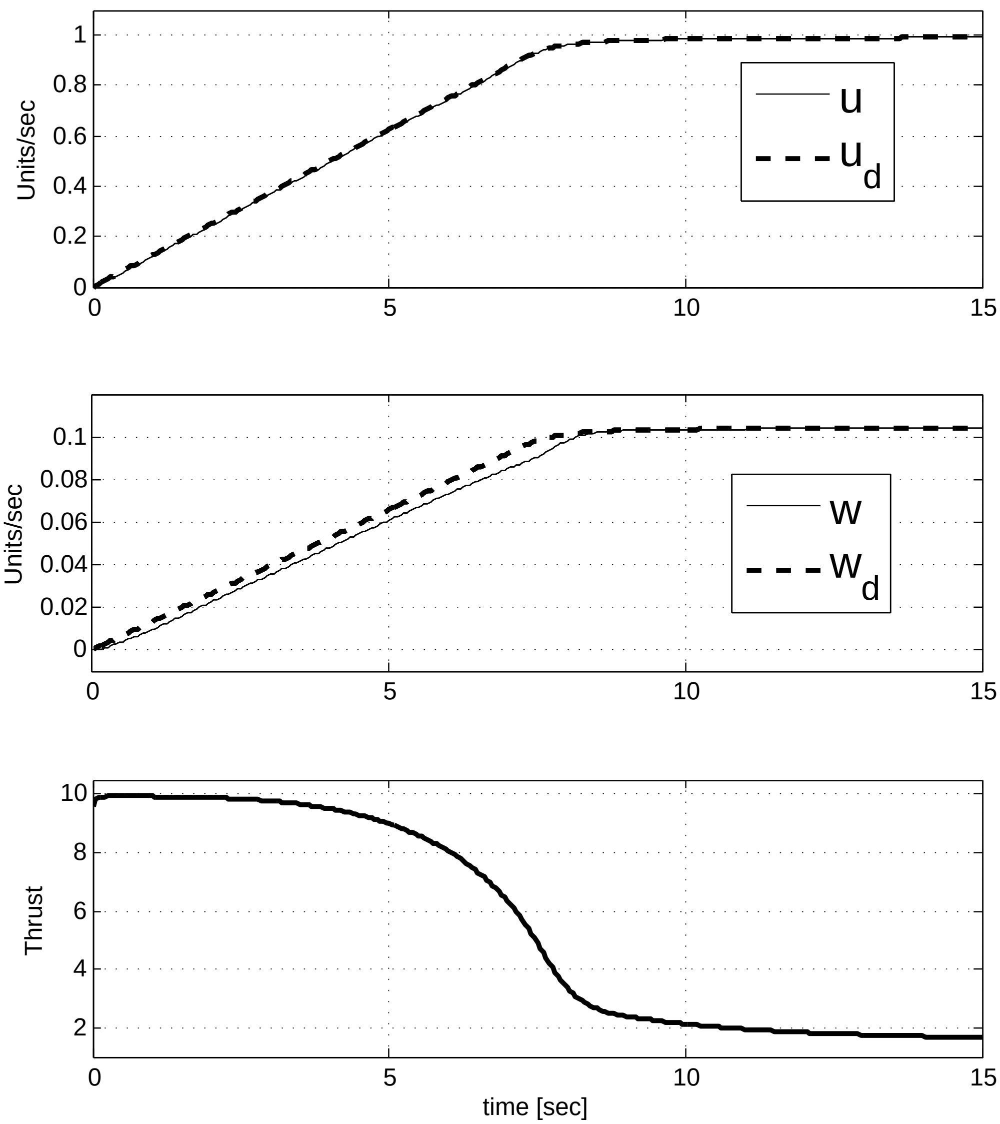


Figure 4.2: u and w velocities during the transition from hover to cruise flight mode, also the thrust output control is presented.

4.2 Cruise to hover flight mode

Now the simulation results for the opposite flight transition are presented with $u = 1$, $w \approx 0$ and $\theta \approx 12$ degrees as the initial conditions. Fig. 4.3 shows the system evolution w.r.t. the desired angle position and its respective AoA. In Fig. 4.4 it can be seen that the velocities decrease at ≈ 0 which corresponds to the hover condition. Same as before, the angle θ_d is a smooth function.

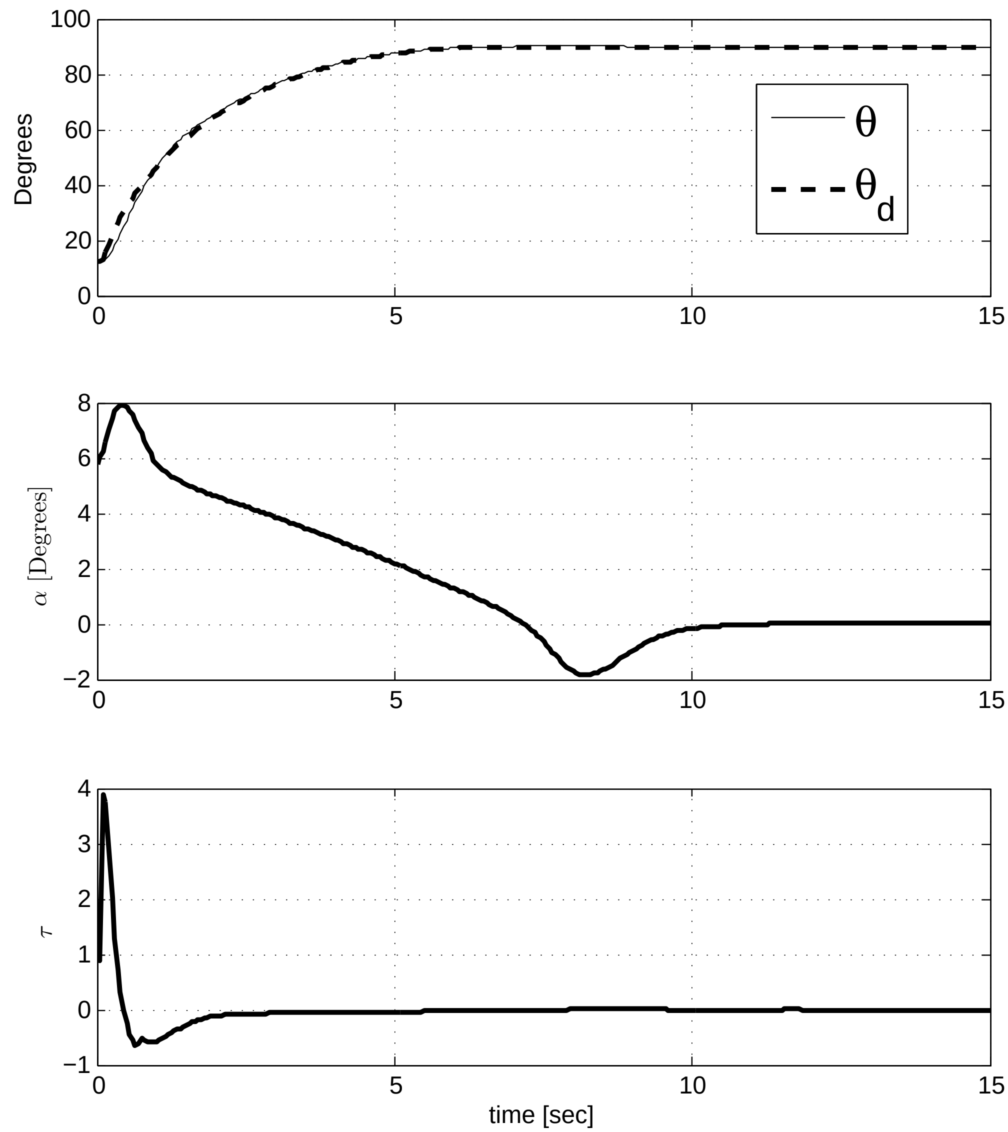


Figure 4.3: Closed-loop system behavior: Cruise to hover flight mode. Variables θ and α angle evolution according to the θ_d signal. Also, this figure presents the control output τ.

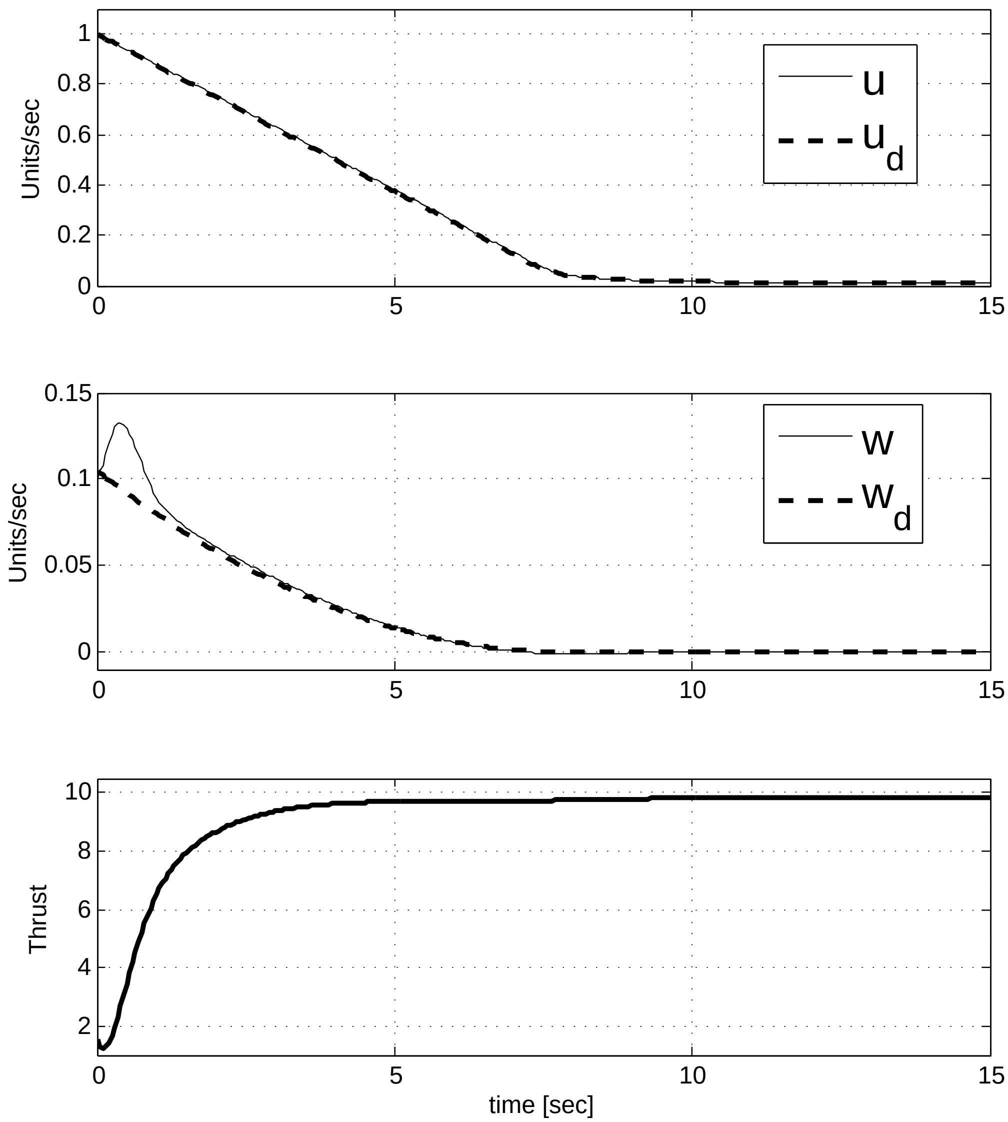


Figure 4.4: *u* and *w* velocities during the transition from cruise to hover flight mode, with its respective thrust output control.

CHAPTER 5

Experimental platform

In the following section a series of experiments will be carried out which include a series of flights with the Tail-sitter convertible UAV. The purpose of these experiments is to analyze the behavior of the drone during the flight and the transition between the two different flight modes (Hover-Cruise). It is worth mentioning that the tests performed were done in a relatively small area, because of what the tests and the results are a bit limited. On the other hand, it is also important to mention that these tests also show the flight efficiency achieved by being able to execute both flight modes with a single UAV.

5.1 UAV specifications

The convertible UAV model chosen is the tail-sitter aircraft, particularly, we have used the fuselage of the Quadshot platform. We have instrumented it in the laboratory with

Figure 5.1: Hybrid UAV implemented and used in the experiments.

several actuators, sensors and microprocessors in order to obtain a reliable platform. A figure of our developed platform is shown at fig.5.1. In table 5.1 are shown the main physical specifications of the used UAV. Some of this factors are really important to determine or adjust gains in the different flight modes.

5.1.1 Flight Control Unit

The ”brain” or flight control of the UAV is made up of both hardware and software, in this case, talking about the hardware, the UAV has a Pixfalcon whose characteristics are:

- 32bit STM32F427 Cortex M4 microprocessor

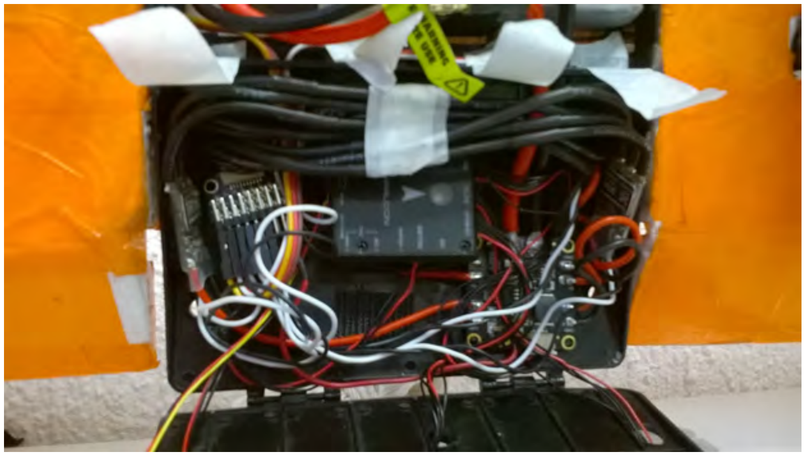
Specification	Value	Unit
Central wing vertical length	17.5	cm
End wing vertical length	14.5	cm
Horizontal wing length	104	cm
Elevon length	4	cm
Max wing thickness	4	cm
Min wing thickness	2	cm
Top motor pair separation	28	cm
Bottom motor pair separation	66	cm
Wing plane-motor separation	9	cm
Motor height	23	cm

Table 5.1: UAV specifications

- IMU (Internal Measurement Unit), which includes gyroscope, accelerometer, barometer
- Communication interfaces

The function that the IMU has in the flight control is to provide to the system a feedback of the current attitude states in order to generate or compute the control outputs that will later be executed by the actuators. This set of sensors allow to know both the orientation of the UAV and its height and angular velocities. As it is well known, the microprocessor has the main function of executing the control algorithm as well as processing the information or data obtained by the IMU; this processor, due to its high speed and capacity to store information, has the capability to run the control algorithms that have been proposed previously, so it is not necessary to include some other processing device.

In fig.5.2(a) the reader can see the internal components of the flight control system consisting of: the aforementioned Pixfalcon flight controller; the power distribution card that energizes the Pixfalcon; and the power systems as the ESC. In fig.5.2(b) the missing components for the flight control system are appreciated. Also the radio receiver and telemetry that maintain the communication with the remote control and the ground station computer respectively, and finally the safety switch is observed which provides safety to the user by preventing the motors to turn causing an accident.



(a) Internal fly control system

(b) External fly control system

Figure 5.2: Flying control system.

5.1.2 Actuators and power systems

The UAV has 6 actuators, four thrust brushless motors and two ailerons that are controlled by servomotors. As it is well known, the brushless motors are controlled by

ESC's (Electronic Speed Control) which generate the appropriate pulses in the appropriate time to achieve a constant rotation speed of the four motors. On the other hand, the main energy distribution card is found, which is responsible for providing from the battery the current necessary for each actuator or motor connected to it. The table 5.2 describes the actuator and power devices used in the UAV.

Device	Brand	Model	Max. Capacity	Unit
Brushless motor	Foxtech	Race edition 2300KV	26.8	Amp
Propeller	Generic	8045		in
ESC	Hobbywing	Micro BLHeli	30	Amp
Servomotors	Tower Pro	MG 90S	1.5	$Kg \cdot m$
Power board	Holybro	PM06-v1.0	30	Amp

Table 5.2: UAV specifications.

The position of the motors in a quadrotor is an important factor in determining the behavior of the UAV, in fig.5.3 are shown the configuration of motors present in the UAV. Due to the small distance between motors opposed by the plane of the wing, the configuration used is in ”V” shape, which implies that it is not completely symmetrical modifying considerably the dynamics of the UAV to perform the maneuvers in hover mode. In the same way, due to the fact that the two pairs of motors divided by the y-axis are very close together, the pitch control becomes a very delicate aspect, since the inertia in that axis is relatively small, allowing sudden movements.

The aileron system is manipulated by servomotors linked with a thin metal bar to push or pull the middle part of the aileron flexing the control surface as can be seen in fig.5.4. To obtain the best response to signals, digital servomotors were used.

Figure 5.3: UAV motor configuration.

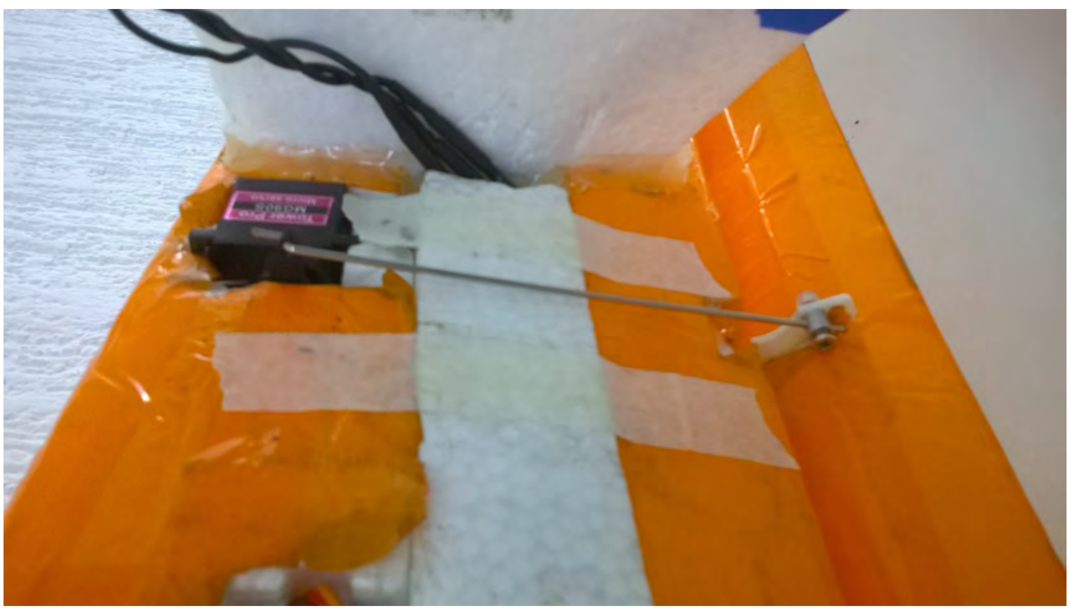


Figure 5.4: UAV aileron mechanism.

5.2 Experiments

Before performing any flight session with the UAV it is recommended to do a previous calibration of all sensors (gyroscope, accelerometer and level). As important is to make sure that the battery has a good level of charge, make sure that the propellers are perfectly fastened and in the correct direction. The verification of the flight modes assigned to a remote control input should also be checked as this will allow us to make the changes in flight mode. It is important to remember the position and the operation of each flight mode, because if an accident occurs the pilot must react in the best possible way to the situation. Once the UAV is located in the flight area and placed vertically in hover mode (UAV initial state) you can continue to energize the UAV, until the flight controller has played the different start sounds, then it is possible to press the security button.

Once the secure button is pressed it is possible and safe to arm the UAV, for doing this, it is necessary, through the radio control, to put the throttle stick to the minimum value in conjunction to the maximum yaw value until the distinctive armed sound is heard. At this time according to the firmware configuration, the motors could begin to spin at low speed or stay off (usual situation at starting stage). Now, it is possible to raise the UAV by increasing, preferably, slowly the throttle stick until reaching a point where the aircraft begins to lift. It is important to keep your eyes on the vehicle since due to weather conditions or control of the system, the UAV could behave in a non desired way. Fig.5.5 shows the flow diagram that represents the flight stages that were carried out during each test. This diagram shows steps from the pre-flight check to the later landing and the UAV disarming. This flow chart should not only be taken into account for the realization of tests, but also it is recommended to do the first two steps in each flight session, in order to avoid accidents.

Once the aircraft has reached an adequate height (greater than 5 meters) it is possi-

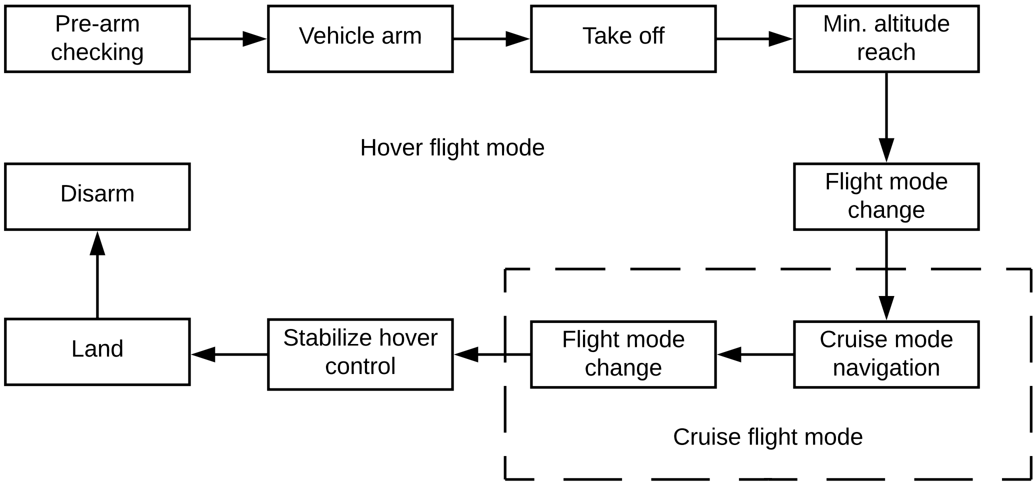


Figure 5.5: Experiment flow diagram showing the flying steps.

ble to change the flight mode. For this, it is essential to have a radio control previously configured with a switch responsible for the flight change between flight modes, as well as having configured the firmware correctly.

5.3 Experimental results

In fig.5.6 a picture of the UAV is shown flying in the cruise mode. In fig.5.7 (a) the displacement graph is shown during a flight test in hover mode within the coordinates x and y in the reference frame. As can be seen, inside this flight mode it is possible to maintain a relatively fixed position during flight, since the propulsion direction is upwards, just like a multi-rotor. In fig.5.7 (b) the displacement in the z axis that was obtained during the same flight test is shown, here it can be appreciated that the height change can be executed without needing to execute large horizontal displacements.

During the tests, different flight transitions were made using one of the established firmwares (X Quadrotor PX4 tailsitter) in order to analyze and compare the behavior of the UAV. In fig.5.9 the displacement in the two different flight modes can be observed,

Figure 5.6: Hybrid UAV flying in hover flight mode

because the place where the test was performed was relatively small, it was not possible to obtain a continuous and long flight session, but it can clearly seen the type of displacement that was made. In the blue line, the movement in the hover flight mode is displayed, where the maneuverability is easily appreciated and it is possible to carry out both horizontal and vertical displacements independently. On the other hand, the red line shows the cruise mode showing that the maneuverability is reduced enough, since in the air, the UAV must maintain a certain longitudinal speed.

Another important graph is the evolution of the pitch angle during this transition, fig.5.10(a) depicts in the blue line the desired angle generated by the control algorithm within the current firmware; red and orange lines are the actual values of the UAV pitch angle during the flight in hover and cruise, respectively.

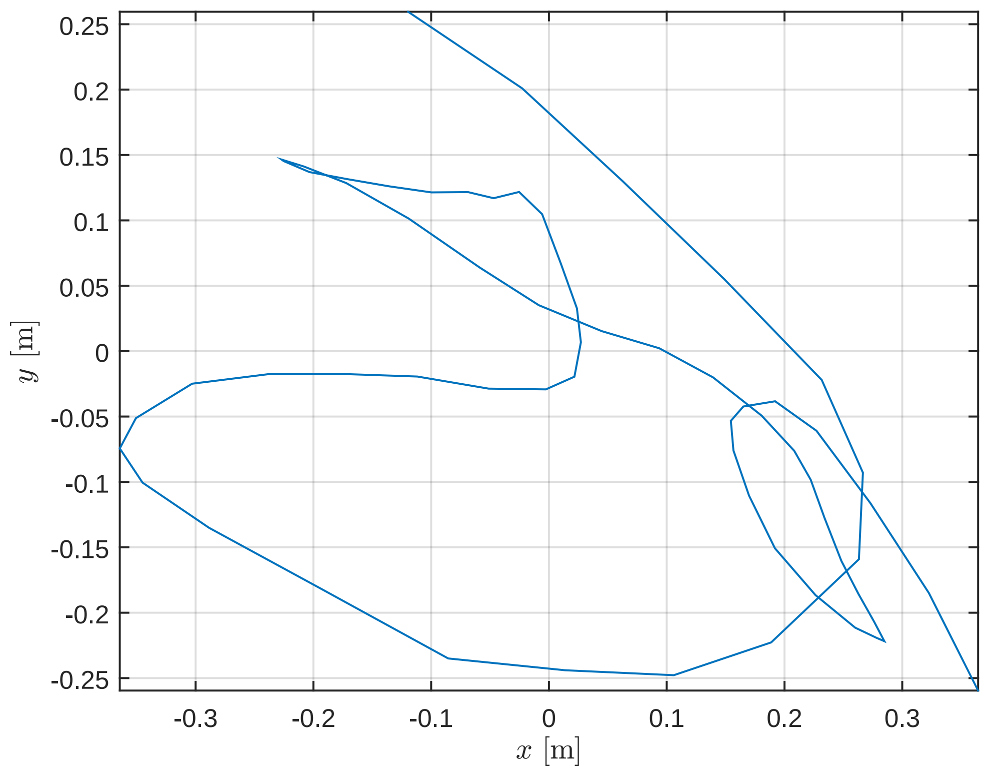
It is clear that the desired value of the pitch angle during the transition is reduced from 0 degrees to approximately -75 degrees in a linear manner. This is due to a different body frame configuration chosen in the real platform. However the magnitude of difference between both angles, 0 and -75, is 75 degrees, a value inside of the predefined range for the transition flying mode. Another important aspect is the evolution of the UAV altitude. In fig.5.10(b) this evolution of the state is shown during the transition of flight mode. At this time the aircraft height is maintained rising during the transition, so it can be assured that the control of the algorithm does not consider maintaining a height during this stage. This factor is very important in our study because during the design of the proposed control it is not intended directly to maintain a constant flight height during the transition.

One of the main advantages of hybrid UAVs is the extended duration of flight time and longer distance travel. This is due to the ability to execute the cruise flight mode, that is to displace at a much higher speed than a multi-rotor and with much less energy consumption. To verify this, some tests were performed in which the flight change was executed. This is shown in fig. 5.11, which compares the energy consumption in relation to the UAV travel speed. It can be seen that during the transition, the energy consumption is maintained at a level equal to the hover flight mode, but comparing this information with the UAV speed during the entire flight session is very different, since when making the transition, the displacement speed increased, thus giving greater coverage of the aircraft distance consuming the same energy. This is in part due to the thrust force, which is concentrated in horizontal direction.

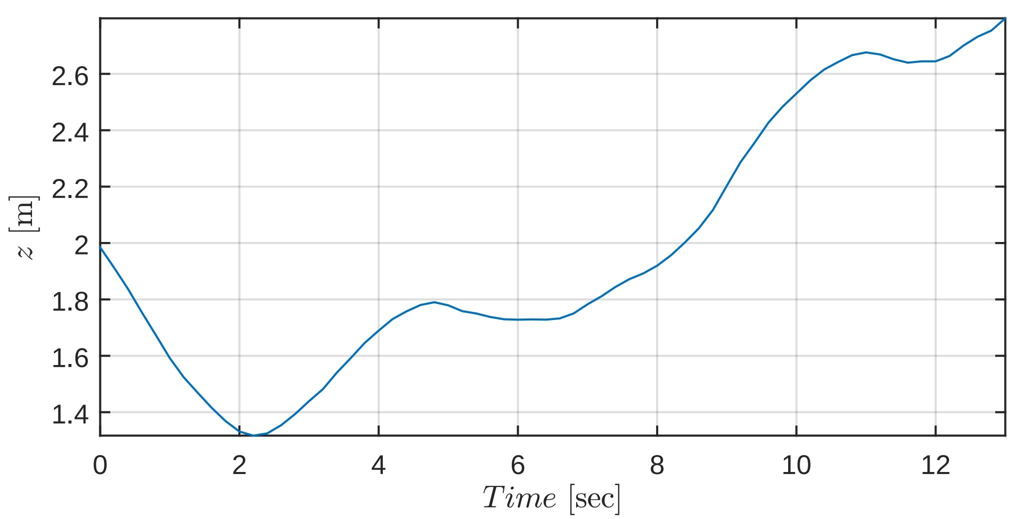
5.4 Discussions

In this chapter some experiments were performed with the hybrid tail-sitter UAV developed at the CIO Perception and robotics LAB. It is shown that the obtained results from during the transitions between the two flight modes were satisfactory. The key points of these tests can be divided into three main aspects: effectiveness, control and security.

Talking about the control, which is one of the most important parts, it is a simplified control, since it is based mainly on the constant inclination in pitch of the UAV having at the end an angle of threshold which defines the conclusion of the transition between the flight modes. Hence it does not really take into account other variables of the system. The speed of inclination can be modified by the user, allowing the transition to be faster or slower depending on the needs. Finally, it can be understood that the safety of the system during the transition is mainly focused on evaluating the altitude and speed of the UAV during this phase, since if during the transition the aircraft goes below a minimum set values, the system returns to hover mode. Knowing this, it is clearly recognizable that the control system does not have the capacity to modify the altitude control of the UAV during the transition if it starts to descend or if unwanted movements are generated due to climatic conditions or of any other type, instead if focuses only on the inclination to achieve the desired position.



(a) Internal fly control system



(b) External fly control system

Figure 5.7: Hover flight mode test graphs results

Figure 5.8: Hybrid UAV flying in cruise flight mode

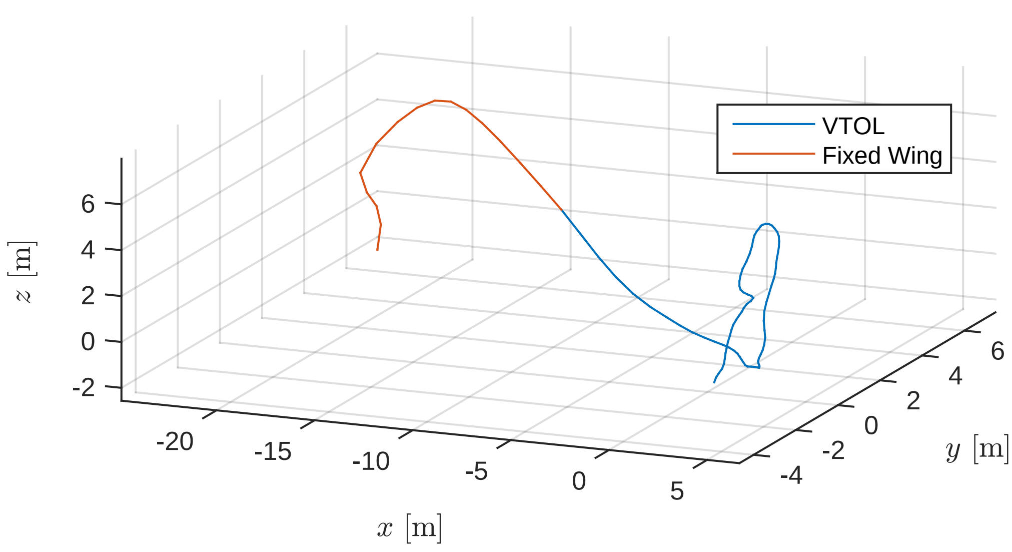
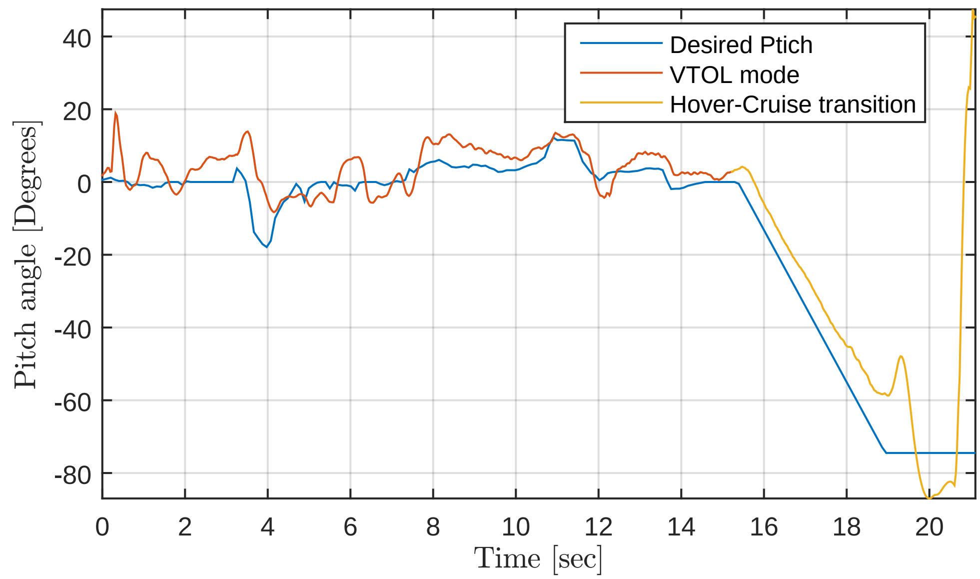
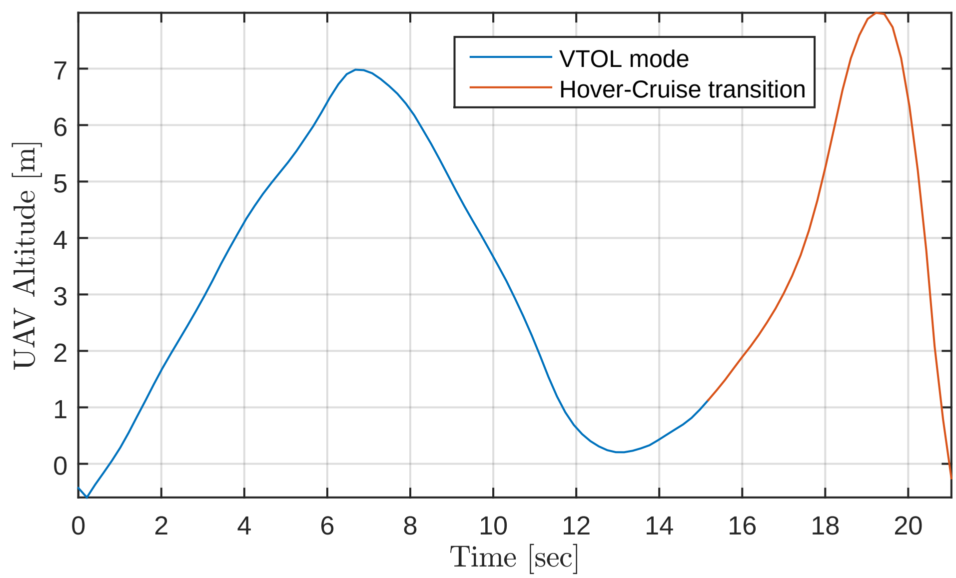


Figure 5.9: Transition mode flight test.

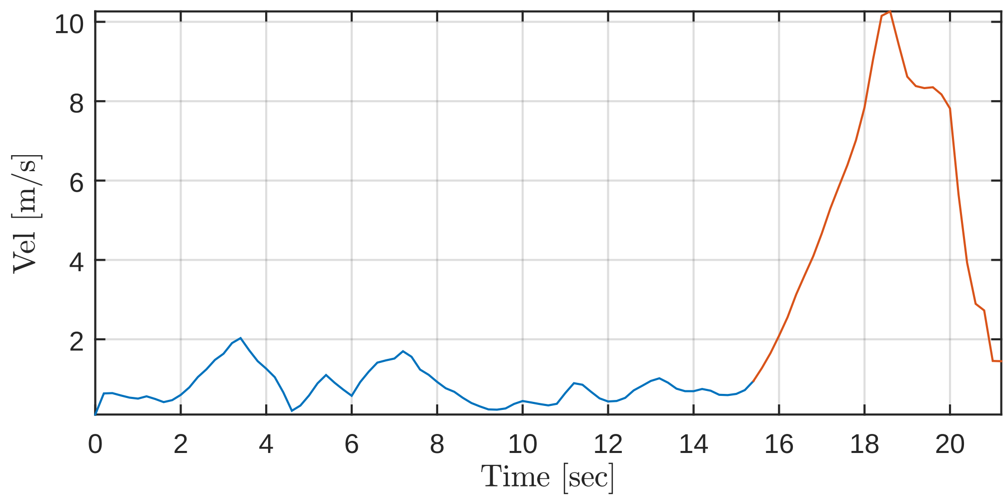


(a) Pitch angle transition change

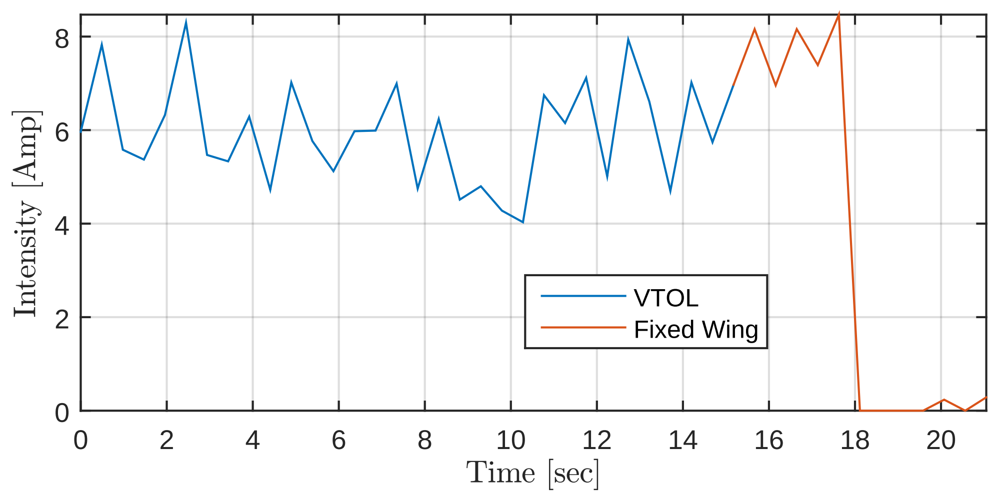


(b) altitude change

Figure 5.10: a) Pitch angle state value during transition test; b) Altitude state during the flight transition test.



(a) Velocity of the UAV



(b) Energy consumption during flight

Figure 5.11: Relation between energy consumption and UAV velocity.

CHAPTER 6

Conclusions

In this document a simplified control strategy for the transition maneuver of the tail-sitter UAV is proposed. Such controller is based on the time-scale separation and the use of saturation functions. The design is based on Lyapunov approach. Simulations demonstrate the effectiveness of the controller for achieving transition from hover to cruise mode and vice-versa. It is important to mention that the controller have the peculiarity that it does not present any switching, it is smooth and it take into account the saturation limits imposed by the actuators. Such characteristics are useful for implementation in a real UAV.

Similarly it was demonstrated the advantage of energy savings and flight optimization to be able to execute both modes of flight (cruise-Hover) and thus be able to perform specific maneuvers according to the situation that occurs.

In a further work, it could be possible to design a more robust control that consider external disturbance as part of the modeling, such as wind gusts. Also, the control can be completed by analyzing the 6-DOF and finally perform a full real simulation an real experiments of the transition control. Also, it is planned to develop the second version of our prototype, intended to be useful in real applications, in particular to highway monitoring using vision and artificial intelligent systems.

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