THE TILT-QUADROTOR: MODELLING AND ATTITUDE STABILIZATION

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Abstract
This paper presents the study on a new type of aircraft, the Tilt-Quadrotor. This multirotor platform differs from classical quadrotors by having four servo motors that tilt two of its four rotors, in two different directions each, allowing the horizontal motion to be executed without tilting the platform. The derived Tilt-Quadrotor model is explained and implemented in a simulator. LQR controllers are designed for attitude and altitude stabilization, and validated in simulation. An approach based on the linearized model is implemented experimentally in a PixHawk autopilot, achieving the stabilization of all three attitude angles of a Tilt-Quadrotor prototype.

1. INTRODUCTION

Unmanned Aerial Vehicles (UAV) are rather popular nowadays, not only as a hobby but also with real world applications, being widely studied. Primarily used in the academia as a medium for testing new control methodologies, a recent trend has given an increasing focus to new types of aircraft with different configurations.

The main motivation is to solve the inherent under-actuation of traditional multirotors, thus allowing a more precise and complete control, which is required by many applications such as surveillance, mapping or inspection operations. An example of experiments made with fully actuated multirotors can be seen in Brescianini and D'Andrea[1].

The Autonomous Locomotion Individual Vehicle (ALIV) approach, based on the patent by Severino Raposo[2], corresponds to the use of four additional servo motors which can tilt, in two different directions, two of the four rotors of the platform. As such, the new platform is overactuated and capable of a greater range of motions, from which the main advantage is the possibility of horizontal motion without the need of tilting the platform central core. Unlike a classical quadrotor, the Tilt-Quadrotor can also maintain its position while in a tilted configuration. One of the prototypes already developed with this configuration can be seen in figure 1.

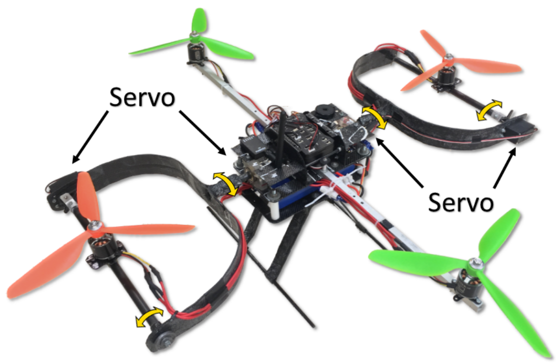

Figure 1: ALIV3 prototype

This paper compares the Tilt-Quadrotor with the classical quadrotor. This analysis, together with the modeling of the Tilt-Quadrotor, including its actuators and sensors, is presented in section 2. With the purpose of achieving attitude and altitude stabilization, LQR controllers are designed and validated in simulation in section 3. The results of the experimental stabilization of the Tilt-Quadrotor are shown

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in section 4. Final conclusions are drawn in section 5.

2. TILT-QUADROTOR MODEL

This section presents the Tilt-Quadrotor model including the dynamics of the actuators (DC motors, servo motors and propellers) and of the sensors which will be used for the simulator developed in MATLAB Simulink. The Tilt-Quadrotor functioning principle is also explained in more detail.

2.1. Coordinate systems

Two reference frames are adopted in this work, according to which the forces, moments and movement of the quadrotor can be described, namely the inertial reference frame and the body-fixed frame, which are shown in Figure 2.

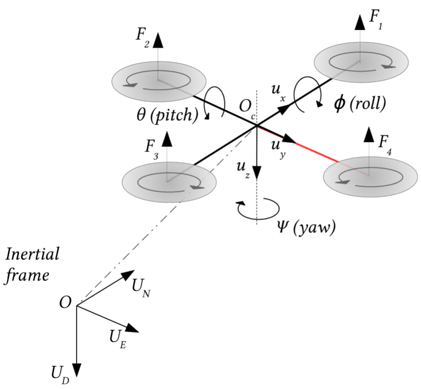


Figure 2: Inertial and Body-Fixed Frames from Esteves[3]

The inertial frame adopted is the North-East-Down (NED) frame, with the frame origin O located on the surface of the Earth at the quadrotor initial position, and with x, y and z axis pointing North, East and Down, respectively. The second frame is fixed at the quadrotor, with origin in its center of gravity O_c, with the u_x axis aligned with rotor 1 (red axis), the u_y axis pointing to the right, and the u_z axis pointing downward. Vectors expressed in the inertial frame are marked with the superscript I and vectors expressed in the body-fixed frame are marked with the superscript B.

2.2. Actuation

There are several actuators in this system. The brushless direct current motors operate in conjunction with electronic speed controllers (ESC). The ESC receive a Pulse Width Modulation (PWM) signal and are thus responsible for the commutation of the motor coils. The ESC are assumed ideal.

The model of the motor can be approximated by a first-order system[4], in which the input PWM signal is related to the motor angular velocity ω_i through the frequency domain model:

$$\frac{\omega_i(s)}{PWM_{m_i}(s)} = \frac{K_{m_i}}{\tau_{m_i}s+1} \tag{1}$$

with K_{m_i} the DC gain of the motor and τ_{m_i} its mechanical time constant.

Similarly, the rotation angle θ_i of the servo motor is related to its input PWM signal by:

$$\frac{\theta_i(s)}{PWM_{s_i}(s)} = \frac{K_{s_i}}{\tau_{s_i}s+1} \tag{2}$$

with K_{s_i} the DC gain of the servo and τ_{s_i} its mechanical time constant.

According to Bouadallah et al.[5], the thrust T_i and the moment Q_i produced by propeller i can be related to the propeller angular speed by:

$$T_i = K_T\omega_i^2 \tag{3}$$

$$Q_i = K_Q\omega_i^2 \tag{4}$$

where K_T and K_Q are the coefficients of thrust and moment respectively, assumed equal for all propellers, and usually obtained experimentally.

2.3. Control allocation

Unlike a classical quadrotor, where opposite rotors rotate in the same direction, the Tilt-Quadrotor requires a different configuration. Consider the example of the Tilt-Quadrotor in the classical configuration, as shown in Figure 3, where the red arrows represent the forces and moments produced by these rotors. Assume all rotors in opposite pairs have the same angular speed, and that the orange rotors rotate in the anticlockwise direction and the green rotors in the clockwise direction. In this case, when the two orange rotors are tilted, this results not only in a desired forward motion due to the forward facing force component, but also in an undesired rotation around the x-axis due to the resulting moment.

In the proposed configuration, represented in Figure 4, the moments produced by the tilted rotors cancel each other, annulling the undesired resulting moment around the x-axis, while maintaining the desired x-axis force.

Figure 5(a) shows the Tilt-Quadrotor when the first servo motors are actuated, tilting rotors 2 and 4 about the x axis by an angle of ϕ_2 and ϕ_4 respectively. The action of the other two servo motors is

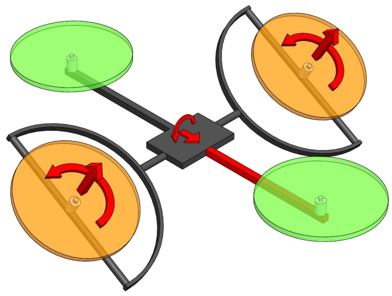


Figure 3: Tilt-Quadrotor x movement with classical quadrotor propeller configuration

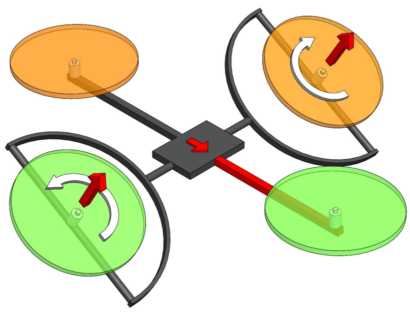
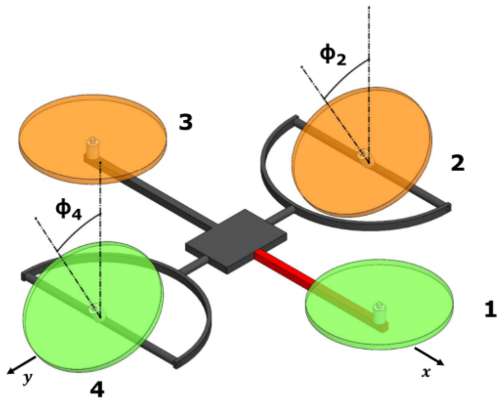
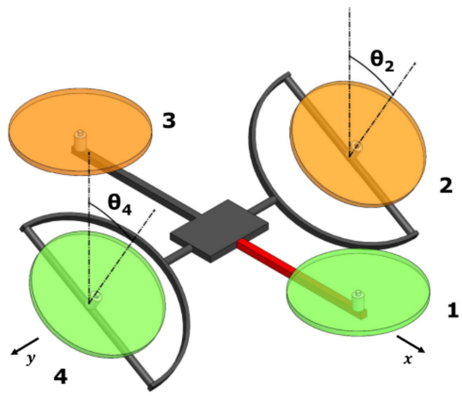


Figure 4: Tilt-Quadrotor x movement with new propeller configuration



(a)



(b)

Figure 5: Tilt-Quadrotor configuration

depicted in Figure 5(b), with the tilting of rotors 2 and 4 this time about the y axis by an angle θ_2 and θ_4 respectively. It should be noted that all 4 servos can move independently and in both directions. As such the control allocation is defined for this new configuration, representing how the resulting forces and moments acting on the Tilt-Quadrotor are related with the thrust and moment produced by each propeller. The resulting propulsion forces and moments produced by the quadrotor are then given by:

$$F_P^B = [F_x, F_y, F_z]^T \tag{5}$$

$$M_P^B = [M_x, M_y, M_z]^T \tag{6}$$

where

$$F_x = -T_2 \sin(\theta_2)\cos(\phi_2) - T_4 \sin(\theta_4)\cos(\phi_4) \tag{7}$$

$$F_y = T_2 \sin(\phi_2)\cos(\theta_2) \tag{8}$$

$$F_z = -[T_1 + T_2\cos(\theta_2)\cos(\phi_2) + T_3 + T_4\cos(\theta_4)\cos(\phi_4)] \tag{9}$$

$$M_x = T_2\cos(\phi_2)\cos(\theta_2)d - T_4\cos(\phi_4)\cos(\theta_4)d + Q_2\sin(\theta_2)\cos(\phi_2) - Q_4\sin(\theta_4)\cos(\phi_4) \tag{10}$$

$$M_y = (T_1 - T_3)d - Q_2\sin(\phi_2)\cos(\theta_2) + Q_4\sin(\phi_4)\cos(\theta_4) \tag{11}$$

$$M_z = -Q_1 + Q_2\cos(\phi_2)\cos(\theta_2) + Q_3 - Q_4\cos(\phi_4)\cos(\theta_4) - T_2\cos(\phi_2)\sin(\theta_2)d + T_4\cos(\phi_4)\sin(\theta_4)d \tag{12}$$

From this set of equations it is possible to find the solutions for the different motions to be performed by the quadrotor.

2.4. Equations of motion

The quadrotor position $\mathbf{P}^I = [x, y, z]^T$ in the inertial frame is related to the velocity in the body-fixed $\mathbf{V}^B = [u, v, w]^T$ frame by (13). The quadrotor attitude is described by the Euler angles $\mathbf{\Phi} = [\phi, \theta, \psi]^T$. The angular velocity is given by $\mathbf{\Omega}^B = [p, q, r]^T$ and is measured in the body-frame, where p, q and r correspond to the angular velocities around the u_x, u_y and u_z axis respectively. The dynamics and kinematics of the Tilt-Quadrotor can be summarized by the following equations in accordance to Stevens et al.[6].

$$\dot{\mathbf{P}}^I = \mathbf{S}\mathbf{V}^B \tag{13}$$

$$\dot{\mathbf{\Phi}}^B = \mathbf{T}\mathbf{\Omega}^B \tag{14}$$

$$m\dot{\mathbf{V}}^B = \mathbf{F}_P^B + m\mathbf{S}^T\mathbf{g}^I - \dot{\mathbf{\Omega}}^B \times m\mathbf{V}^B \tag{15}$$

$$\mathbf{I}\,\dot{\mathbf{\Omega}}^B = \mathbf{M}_P^B - \mathbf{\Omega}^B \times \mathbf{I}\,\mathbf{\Omega}^B \tag{16}$$

where $\mathbf{I}$ is the inertia matrix and $\mathbf{S}$ is the rotation matrix that transforms a vector in the body-fixed frame to the inertial frame and is obtained by:

$$\mathbf{S}(\mathbf{\Phi}) = \mathbf{S}_z(\psi)\mathbf{S}_y(\theta)\mathbf{S}_x(\phi) \quad (17)$$

The transformation matrix $\mathbf{T}$ relates the angular velocity in the body-fixed frame with the Euler angle rates[7] and is given by:

$$\mathbf{T} = \begin{bmatrix} 1 & \sin(\phi)\tan(\theta) & \cos(\phi)\tan(\theta) \\ 0 & \cos(\phi) & -\sin(\phi) \\ 0 & \sin(\phi)\sec(\theta) & \cos(\phi)\sec(\theta) \end{bmatrix} \quad (18)$$

2.5. Sensors

The autopilot board of the prototype is equipped with an InvenSense MPU-600 inertial measurement unit (IMU) which has a 3-axis accelerometer, a 3-axis gyroscope, a 3-axis magnetometer and a barometer.

2.5.1. Accelerometer

The accelerometer readings can be simplified through calibration for a near hovering situation (see Mahony et al.[8]) to:

$$\bar{\mathbf{a}}^B = \mathbf{S}^T\mathbf{g}^I + \dot{\mathbf{\Omega}} \times \mathbf{r} + \mathbf{\Omega} \times (\mathbf{\Omega} \times \mathbf{r}) + \boldsymbol{\mu}_a \quad (19)$$

where $\boldsymbol{\mu}_a$ is the accelerometer Gaussian noise and $\mathbf{r} = [r_x, r_y, r_z]$ is the distance of the IMU to the platform center of gravity (CG).

2.5.2. Gyroscope

As in Euston et al.[9], the gyroscope readings are modelled as:

$$\bar{\mathbf{\Omega}}^B = \mathbf{\Omega}^B + \boldsymbol{\mu}_g \quad (20)$$

with $\boldsymbol{\mu}_g$ the gyroscope Gaussian noise.

2.5.3. Magnetometer

According to Esteves[3], the magnetometer readings can be simplified through proper calibration to:

$$\bar{\mathbf{N}}^B = \mathbf{S}^T\mathbf{N}^I + \boldsymbol{\mu}_m \quad (21)$$

where $\mathbf{N}^I$ is the earth magnetic field vector and $\boldsymbol{\mu}_m$ the Gaussian measurement noise.

2.5.4. Barometer

The barometer reading is given by:

$$\bar{p} = p_0 * (1 - \frac{h}{44330})^{5.255} + \mu_b \quad (22)$$

where all variables are in International System units, p_0 is the atmospheric pressure at sea level , h is the altitude of the quadrotor and μ_b is the measurement Gaussian noise.

2.6. ALIV3

The ALIV3 prototype weighs 1903g and its moments of inertia, identified by Mateos[10], are presented in Table 2.6:

Table 1: Platform moments of Inertia

Inertia	$[kg \cdot m^2]$
I_{xx}	0.0367
I_{yy}	0.0262
I_{zz}	0.0504

where these are the values of the diagonal inertia matrix $\mathbf{I}$ introduced in (16).

2.7. Tilt-Quadrotor Simulator

The previously presented equations of motion of the Tilt-Quadrotor and the models of its actuators and sensors were implemented in a simulator developed in MATLAB Simulink, represented in Figure 6, in order to study the behaviour of the platform. The reference signals of the controller block (in red) are sent to the blocks of the DC motors and servo motors (in light blue and yellow respectively). These two blocks contain the dynamics of the actuators and other non-linearities like saturations, quantization and dead-zones. In turn, the individual rotor velocities and the tilting angles are inputs of the TiltQuad block (in green), which includes the control allocation and the nonlinear equations of motions of the Tilt-Quadrotor. The states of the platform are then used in the Sensors and Estimation block (in gray) which models the sensors, including nonlinearities such as quantization, saturation and noise, and estimation algorithms.

3. CONTROL DESIGN

This section describes the development of control solutions for the attitude and position control of

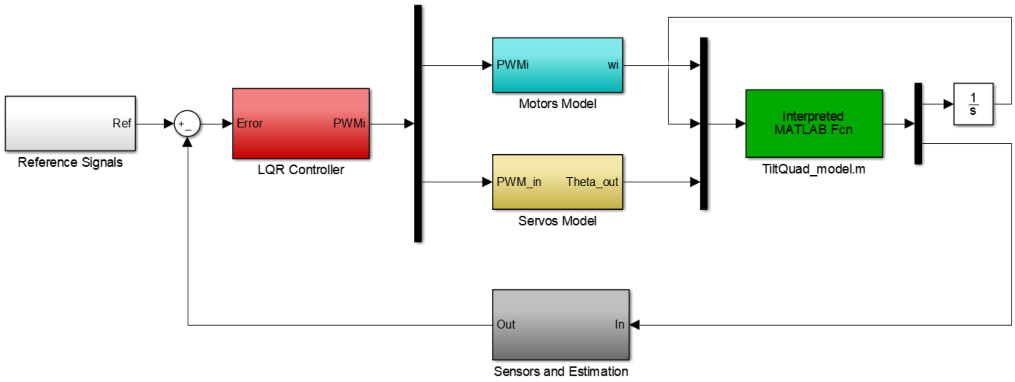


Figure 6: Tilt-Quadrotor simulator

the Tilt-Quadrotor. The models of the actuators and the kinematics and dynamics models of the Tilt-Quadrotor, presented in section 2, can be linearised into a state-space model:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \tag{23}$$

with the state $\mathbf{x} = [\mathbf{\Omega}^T, \dot{\mathbf{P}}^T, \mathbf{\Phi}^T, \mathbf{P}^T]^T$ representing variations around the trim condition considered for linearization.

This is also the case of the input vector, given by:

$$\mathbf{u} = [T_1^m, T_2^m, T_3^m, T_4^m, T_1^s, T_2^s, T_3^s, T_4^s]^T \tag{24}$$

with all the eight PWM inputs, where the first four correspond to the DC motors, and the last four correspond to the four servos responsible for the tilting angles ϕ_2, ϕ_4, θ_2 and θ_4 respectively. The state and input matrices are:

$$\mathbf{A} = \begin{bmatrix} 0_{3\times3} & 0_{3\times3} & 0_{3\times3} & 0_{3\times3} \\ 0_{3\times3} & 0_{3\times3} & 0_{3\times3} & 0_{3\times3} \\ I_{3\times3} & 0_{3\times3} & 0_{3\times3} & 0_{3\times3} \\ 0_{3\times3} & I_{3\times3} & 0_{3\times3} & 0_{3\times3} \end{bmatrix} \tag{25}$$

$$\mathbf{B} = \begin{bmatrix} 0 & 6.7 & 0 & -6.7 & 0 & 0 & 0.8 & -0.8 \\ 6.7 & 0 & -6.7 & 0 & -0.8 & 0.8 & 0 & 0 \\ -0.5 & 0.5 & 0.5 & -0.5 & 0 & 0 & -6 & 6 \\ 0 & 0 & 0 & 0 & 0 & 0 & -0.5 & -0.5 \\ 0 & 0 & 0 & 0 & 0.5 & 0.5 & 0 & 0 \\ -0.4 & -0.4 & -0.4 & -0.4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} * 0.01 \tag{26}$$

where $I_{3\times3}$ is the identity matrix.

The resulting controllability matrix has rank 12, thus proving that the system is fully controllable, as expected, and showing the advantages of this configuration with respect to the classical quadrotor one. However, given the sensors available, the x and y positions and their respective velocities cannot be obtained and will be assumed as known (in the simulator they correspond to the respective ideal states). One interesting observation of matrix **B** in (26) is that the yaw motion, represented by its angular rate in line 3, is about 10 times more sensitive to the motion of servo motors 3 and 4, than to the speed of each of four DC motors. Furthermore, the servo motors influence on yaw is comparable to the influence of the DC motors on the roll and pitch motions. As such, it is predicted that the yaw motion of the Tilt-Quadrotor could be almost as fast as roll and pitch motions, unlike classical quadrotors where the yaw motion is considerably slower.

Lastly, it should be noted that the linearized model leads to some loss of information regarding the nonlinear model of the Tilt-Quadrotor. In the nonlinear model, and as noticed in (9), any tilting of the rotors will lead to a decrease in the vertical component of thrust, thus having a negative impact in the quadrotor vertical acceleration. However, this influence is not present in the linear model as can be seen by the zeros in the last four columns of the fourth row of matrix **B** in (26).

3.1. Attitude control

A linear quadratic regulator (LQR) controller was designed for attitude control, using the following weight matrices, where $diag()$ indicates a diagonal matrix:

(27a)
$$\mathbf{Q}_{\text{att}} = diag([750, 1000, 450, 7000, 10500, 800]);$$

(27b)
$$\mathbf{R}_{\text{att}} = diag([1, 1, 1, 1, 5, 5, 5, 5] * 0.01);$$

The first three elements of $\mathbf{Q}_{\text{att}}$ are in $[(s/rad)^2]$ and the last three in $[rad^{-2}]$, while the elements of $\mathbf{R}_{\text{att}}$ are all in $[\mu s^{-2}]$. Since roll and pitch angles are crucial for stabilization, a larger weight is attributed to these states when compared to the yaw angle.

The performance of the LQR attitude controller is accessed through simulation tests in which all three attitude angles are required to follow a 5 degree step response. It should be noted that in these tests ideal sensors were considered. Figure 7 presents the results obtained.

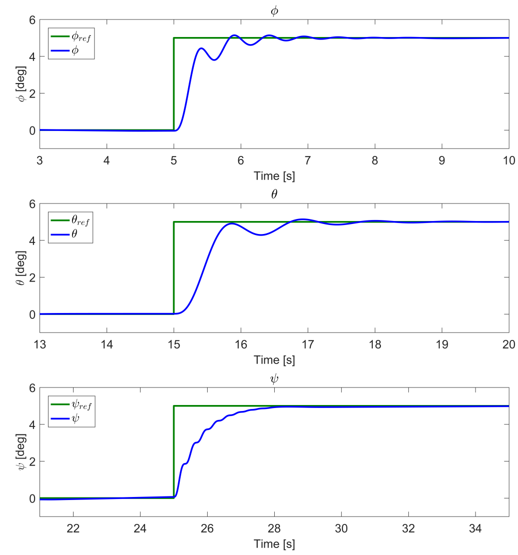


Figure 7: Attitude control response to step references

The obtained responses have slight oscillations but the three angles responses are fast and with no static errors. As imposed by the choice of the weights in $\mathbf{Q}_{att}$, the roll and pitch angles have a faster response, considering that the yaw angle is not essential for stabilization.

Figure 8 shows the Tilt-Quadrotor response to an unfavourable initial position with a roll angle of $-15°$ and a pitch angle of $15°$. The Tilt-Quadrotor performs well and manages to reach a stable position in a few seconds.

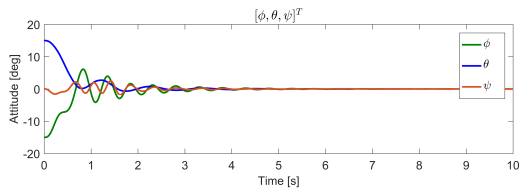


Figure 8: Tilt-Quadrotor performance to an unfavourable initial position

3.2. Altitude control

A LQR controller was also designed for altitude control using the following weight matrices:

(28a)
$$\mathbf{Q}_{\text{alt}} = diag([2500, 10000]);$$
(28b)
$$\mathbf{R}_{\text{alt}} = diag([1, 1, 1, 1, 1, 1, 1, 1] * 0.01);$$

where the elements of $\mathbf{Q}_{\text{alt}}$ are in $[(s/m)^2]$ and $[m^{-2}]$ respectively, and the elements of $\mathbf{R}_{\text{alt}}$ are in $[\mu s^{-2}]$. The respective simulation response to an 1m step input is shown in Figure 9.

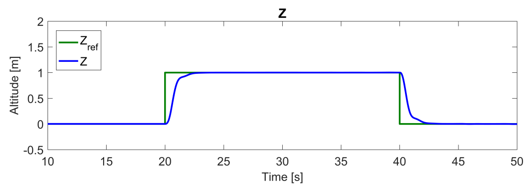


Figure 9: Altitude control response to a step reference

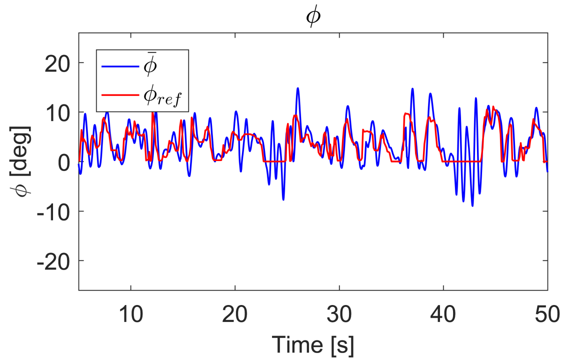
4. EXPERIMENTAL RESULTS

The final goal of this work is to implement the designed controllers in the ALIV3 prototype shown in Figure 1. At the time of this publication, only the attitude controller was implemented and tested. This section therefore presents the experimental implementation and respective results of the attitude Tilt Quadrotor stabilization.

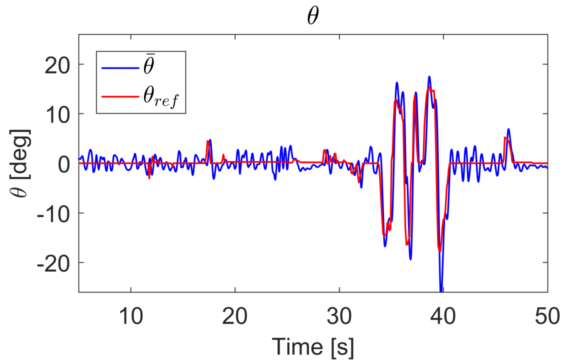
The linearised model of the Tilt-Quadrotor was implemented in a Pixhawk autopilot board with a modified version of the PX4 flight stack. Figure 10 shows the attitude results of the platform testing in a robotics arena.

The ALIV3 has a tendency to drift to the left and as such a small positive tilt is required to maintain position. This is mostly due to vibrations in the main arms, or a bad trim point in one of the servos. Nonetheless the response is fast and accurate, although with overshoots and oscillations which can be reduced with fine tuning.

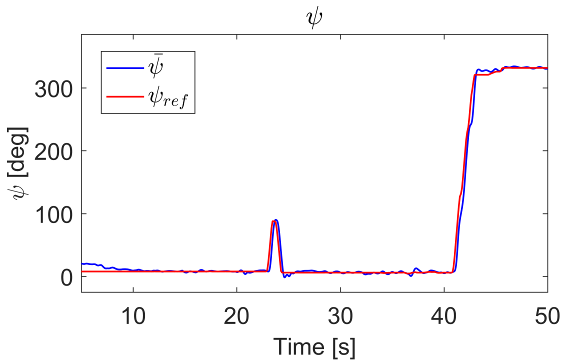
The platform does not drift forward nor backwards and as such the pitch angle has a more stable reference and thus a more stable response. The forward and backward motion of the platform was tested, albeit with the classical configuration achieved by the tilting of the central core, as can be seen in figure 10(b) around the 35s to the 40s mark. The platform travelled several metres forward, stopped, and then travelled backwards, once again reaching a stable position.



(a) Roll angle ϕ response



(b) Pitch angle θ response

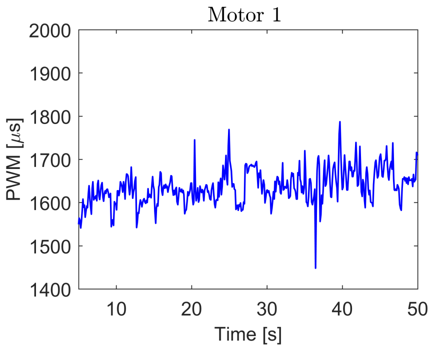


(c) Yaw angle ψ response

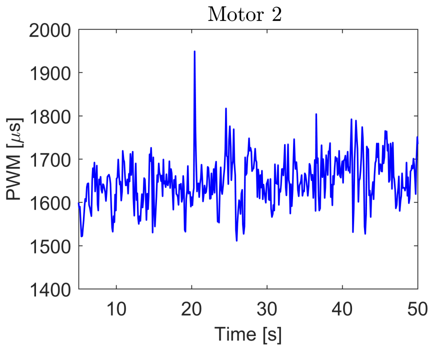
Figure 10: Attitude response of the ALIV3

The platform also responds well to yaw commands, keeping its yaw angle close to the reference, being only slightly affected from the controlling motions of the other angles, meaning that the linearised model is a good approximation. Special attention should be given to the variations around 23s and 42s in Figure 10(c). The first variation corresponds to a yaw rotation command of about $90°$, which is then quickly reversed. The platform performs this motion at speeds reaching $200°/s$. The second variation corresponds to a full rotation about the z axis in one quick continuous motion. Once again the platform performs this motion with high speeds.

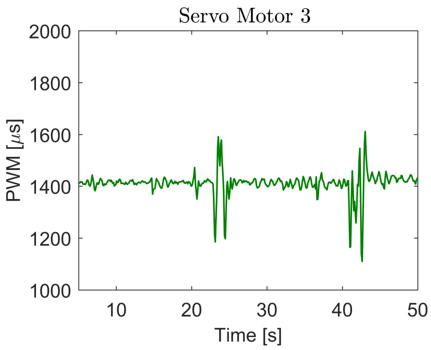
Figure 11 shows the PWM signals sent to two DC motors and two servo motors. There is a clear correlation between the yaw angle shown in Figure 10(c) and the servo signals in Figures 11(c) and 11(d). As expected, the actuation of servos 3 and 4 is symmetrical for a yaw motion. The servo motors 3 and 4 are also required to maintain a yaw moment balance, whenever the platform performs a roll motion.



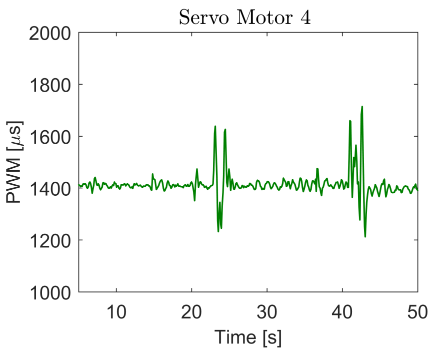
(a) DC motor 1 PWM signal



(b) DC motor 2 PWM signal



(c) Servo Motor 3 PWM signal



(d) Servo Motor 4 PWM signal

Figure 11: PWM actuation signals

Figure 12 shows the ALIV3 in stable flight, during the flight tests which results are presented.

Figure 12: ALIV3 in stable flight

5. CONCLUSIONS

This paper presents a new concept of tilt quadrotor, and the respective platform ALIV3. The Tilt-Quadrotor nonlinear model was derived, including the model of its actuators and sensors. Attitude and altitude controllers, based on the linearized model, were designed and validated on the developed simulator. All three attitude angles have a response in accordance with the defined requirements.

An attitude controller based on the linearized model was implemented in the ALIV3 prototype, and experimentally validated. The results show the platform can achieve stabilization for all three attitude angles. Moreover, the results demonstrate the advantages of this new type of quadrotor configuration when compared with the classical one, namely relative to its ability to perform horizontal motions without tilting its central core, as well as its full controllability.

6. ACKNOWLEDGMENTS

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7. BIOGRAPHIES

7.1. Ricardo Marques

Ricardo Marques is a Msc Graduate in Mechanical Engineering from Instituto Superior Técnico, with a major in Systems and Control. His Master's Thesis had the goal of studying, modelling and controlling a Tilt-Quadrotor. His research is focused on innovative aircraft not only in simulation scenarios but also regarding experimental implementation and validation.

7.2. Alexandra Moutinho

Alexandra Moutinho research interests are focused on mobile robotics, with special emphasis on unmanned aerial vehicles (UAVs). Her main research concerns the different aspects of UAVs, like modelling, simulation, estimation, and control. Being actively involved in the development of different aerial platforms like airships and quadcopters, her research combines both theoretical and experimental developments. She has an active collaboration with other international research groups working in the field of UAVs, namely DRVC/CTI, UNICAMP and UFAM in Brazil and FSD-TUM in Germany, as well as a strong ongoing cooperation with different Portuguese UAV companies like TEKEVER, Spin.Woks, UAVision and ProDrone.

7.3. Filipe Cunha

Filipe Szolnoky Cunha obtained his Mechanical Engineering degree in 1990 at Instituto Superior Técnico, followed by a diploma course at the von Karman Institute in Belgium and the PhD in Applied Sciences at Free University of Brussels. Worked for 6 years at OGMA, Indústria Aeronaútica de Portugal where he was responsible of projects with companies like Dassault, Boeing and Pilatus. At the same time he entered the faculty at Instituto Superior Técnico where he has the responsibility of courses in Mechanical and Aerospace Engineering. He specialized in rotary wing aerodynamics area where he focus his research activities.