26th International Congress of Mechanical Engineering
November 22-26, 2021, Virtual Congress, Brazil

COB-2021-1791
STABILIZATION AND CONTROL OF A QUADCOPTER IN PHYSICAL AND SIMULATED SYSTEMS

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Abstract. *One of the biggest challenges in the development of a quadcopter, also known as a UAV (unmanned aerial vehicle), is the development of a control system that provides good stability during its flight. This article aims to present a control law that can stabilize the flight of a quadcopter. For this, its mathematical model was built using the Euler-Lagrange equations. Subsequently, the model for the development of the controller based on the cascade control strategy was linearized, which consists of proportional, integral and derivative (PID) control actions. The intention was to design a control that can have maximum stability in flight from the construction of the mathematical model to the test in a real environment. This work presented since the control design of a UAV, from its mathematical model, to the implementation of the controller in the physical model, the responses of the simulated model and the physical model are graphically compared.*

Keywords: mathematical model, cascade system, microcontroller

1. INTRODUCTION

Quadcopters, also known as UAVs (Unmanned Aerial Vehicle), has in their control systems an area of investigation for many engineers, as there are several challenges to be solved and studied. As a quadcopter doesn't has a good aerodynamic structure, designing its controller is not a very easy task (Nguyen NP, Huynh TT, Do XP, Xuan Mung N and Hong SK, 2020).

One of its biggest problems is to achieve good stability in flight without the need for high energy expenditure. In return, a quadcopter has the ability to fly in confined spaces, the ability to take off and land vertically, and the ability to hover at a fixed point during flight. In this way, its functions allow the replacement of human work in several complex tasks, whether civil or military, even more in dangerous environments.

For control design, the cascade PID controller is often the most used (N. Bao, X. Ran, Z. Wu, Y. Xue and K. Wang, 2017), (EA Paiva, JC Soto, JA Salinas and W. Ipanaqué, 2015), (A. Astudillo, P. Muñoz, F. Álvarez and E. Rosero, 2017), as its development as well as its implementation in microcontrollers is relatively simple. In (Kyaw M.T. and A.I. Gavrilova, 2016), a PID controller is designed using Ardupilot, where the entire process of implementing controllers for roll, pitch and yaw in a microcontroller is detailed.

In addition to the use of the cascade PID controller, there are studies that perform the stabilization of a quadcopter with the use of more robust controllers, such as adaptive controllers and the use of systematic parameter control to achieve stable flights (Viswanadhapalli P. and Anju SP, 2016).

In this work, the project of PID controllers for the attitude control of a quadcopter was carried out, where the control loops designed in a microprocessor were implemented. Thus, the results of the simulations of the design of control loops in a MATLAB/Simulink environment and the results obtained with the implementation of the controller developed in a microcontroller are presented.

2. PROBLEM STATEMENT

The study carried out in this article is the design of controllers using classical control theory. However, for this, the mathematical model of the quadcopter that will be used is needed. Then, the model is developed and from it the control project begins, to later be embedded in the quadcopter microcontroller. Through simulations with the controller and the mathematical model in MATLAB/Simulink environment, it is possible to verify if the requirements used for the project were satisfied.

As the ultimate goal is to control the attitude (roll, pitch, yaw) of a quadcopter in a real environment, it will be necessary to implement the controller developed in a microcontroller and ship it to the UAV. However, in addition, it is necessary to make the embedded system capable of reading the sensors, capturing the input signal (which will come from a radio control) and sending the command signal to the engines.

Once the design of the controllers is carried out and the code is embedded in the microcontroller, a reference input is generated to carry out the attitude control in the mathematical model and in the physical model. The responses are analyzed and compared in order to verify if stability was achieved. For a better understanding of the approach of the study carried out, see Figure 1.

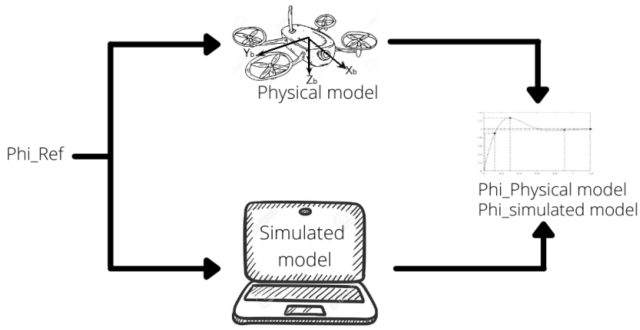

Figure 1. Reference Systems.

2.1 Mathematical model

For the design of the controllers, a simulation in MATLAB/Simulink is necessary in order to know the behavior and responses of the quadcopter, because in this way, there is greater security when embedding the projected code in the physical model, in order to avoid damage to people, structures or the UAV itself.

It is important to carry out the mathematical model taking into account all the physical characteristics of the quadcopter. Its dynamic motion has six degrees of freedom (6DoF) where attitude angles are caused by small changes in the speeds of its four engines. The rotation of two motors is clockwise and the other two is counterclockwise. This is necessary to prevent the quadcopter from rotating around itself, continuously varying its yaw angle.

The forces acting on the vehicle vary according to the rotation speed of the engines. By increasing or decreasing the speed of the motors in a coordinated way, certain movements can be performed. For example, by increasing the speeds of all engines equally, the quadcopter will raise its attitude, as there is an increase in the thrust force without rolling.

To perform a rotational movement around the X axis, known as a rolling movement, the forces generated by motor pair 1 and 2 and motor pair 3 and 4, as shown in Figure 2, must be made unbalanced. Thus, increasing the rotation speeds of motors 1 and 2 in relation to 3 and 4 equally and simultaneously, the quadcopter will perform a rotation around the X axis.

For a rotational movement around the Y axis, known as a lifting movement, the forces generated by motor pair 3 and 2 and pair 4 and 1 must be made unbalanced. Thus, increasing the rotation speeds of motors 3 and 2 in relation to 4 and 1 at the same time, the quadcopter will rotate around the Y axis.

Lastly, movement on the Z axis, known as yaw movement, must cause the forces generated by motor pair 3 and 1 and pair 4 and 2 to be unbalanced. Therefore, by increasing the rotation speeds of motors 3 and 1 in relation to 4 and 2, the quadcopter will perform a rotation around the Z axis.

Figure 2 shows the positioning of the quadcopter motors, where it is possible to visualize the work configuration in “X” responsible for the movement of the UAV.

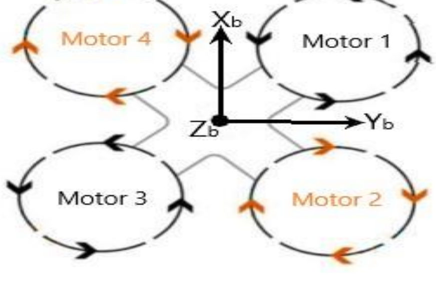

Figure 2. "X" configuration of the quadcopter.

To understand the mathematical model of the quadcopter, information about the values of various parameters is necessary, some of which were calculated and others obtained from the available literature, which were chosen because of their similarity with the study carried out. These values are shown in Table 1.

Table 1. Parameter table.

Parameters	**Names**	**Units**	**References**
Ixx	Inertia on the X axis	0.05(kgm^2)	Author
Iyy	Inertia on the Y axis	0.05(kgm^2)	Author
Izz	Inertia on the Z axis	0.24(kgm^2)	Author
Ω	Ômegas (Engine speed)	15330 (rpm)	Author
Jr	Motor inertia	1.2670e-04 (kg-m^2)	(Diego, 2015)
q	Drag moment	104.10^-6(kg-m^2)	(Ernesto, 2016)
d	Drag Factor	1.1*10^-6	(Ernesto, 2016)
l	Quadcopter Arm Distance	0.56(m)	Author
b	Impulse Factor	54.2*10^-6(kg-m)	(Ernesto, 2016)

For the rotation and translation equations belonging to the mathematical model of the quadcopter, the literature was used as reference (S. Bouabdallah, 2006) and (S. Bouabdallah and R. Siegwart, 2007) with the constants in Table 1. The equations of rotation and translation are shown in Equations 1 to 6.

Rotation equations:

$$\ddot{\Phi} = \frac{I_{yy} - I_{zz}}{I_{xx}} * \dot{\theta} * \dot{\Psi} + \frac{J_r * q * (\Omega_1 + \Omega_3 - \Omega_2 - \Omega_4)}{I_{xx}} + \frac{b * l * (\Omega_2 + \Omega_4)}{I_{xx}} \tag{1}$$

$$\ddot{\theta} = \frac{I_{zz} - I_{xx}}{I_{yy}} * \dot{\Phi} * \dot{\Psi} + \frac{J_r * q * (-\Omega_1 - \Omega_3 + \Omega_2 + \Omega_4)}{I_{yy}} + \frac{b * l * (\Omega_3 + \Omega_1)}{I_{yy}} \tag{2}$$

$$\ddot{\Psi} = \frac{I_{yy} - I_{zz}}{I_{zz}} * \dot{\theta} * \dot{\Phi} + \frac{d * (\Omega_1 - \Omega_3 + \Omega_2 - \Omega_4)}{I_{zz}} \tag{3}$$

Translation equations:

$$\ddot{X} = \frac{1}{m} * \left(\cos(\Psi) * sen(\theta) * \cos(\Phi) + sen(\Psi) * sen(\Phi)\right) * U_2 \tag{4}$$

$$\ddot{Y} = \frac{1}{m} * \left(\text{sen}(\Psi) * sen(\theta) * \cos(\Phi) - cos(\Psi) * sen(\Phi)\right) * U_3 \tag{5}$$

$$\ddot{Z} = -g + \frac{1}{m} * \left(cos(\theta) * cos(\Phi)\right) * U_4 \tag{6}$$

With the above equations, it can be seen that the rotation change parameters are caused by the movement of the motors due to their speed change. Therefore, the variables U2, U3 and U4 are responsible for the movement of the quadcopter.

U_1 is defined as the command related to the translation movement of the quadcopter on the Zb axis upwards, so this variable is related to the altitude variation resulting from the parity of motor speeds, its equation is represented by Equation 7, shown below:

$$U_1 = (\Omega_1 + \Omega_2 + \Omega_3 + \Omega_4) \tag{7}$$

U_2 is the command related to the translation movement of the quadcopter on the Xb axis where is varied the attitude angle in roll, Φ. This is done by increasing the rotation speeds of motors 3 and 4 in relation to the speeds of motors 1 and 2. The U_2 command is represented according to Equation 8, shown below:

$$U_2 = (\Omega_1 + \Omega_2 - \Omega_3 - \Omega_4) \tag{8}$$

The command related to the translation movement of the quadcopter on the Yb axis is U_3, so is varied the attitude angle in pitch, θ. This is accomplished by increasing the rotation speeds of motors 1 and 4 in relation to the speeds of motors 2 and 3. This command is represented according to Equation 9, shown below:

$$U_3 = (\Omega_1 + \Omega_4 - \Omega_2 - \Omega_3) \tag{9}$$

Finally, the U_4 command is related to the rotation movement of the quadcopter on the Zb axis, in which is varied the attitude angle in yaw, Ψ. This is achieved by increasing the rotation speeds of motors 1 and 3 in relation to the speeds of motors 2 and 4. Equation 10 represents this command, which can be seen below:

$$U_4 = (\Omega_1 + \Omega_3 - \Omega_2 - \Omega_4) \tag{10}$$

3. PROJECT DEVELOPMENT

Once with the rotation and translation equations of the quadcopter mathematical modeling, it applyed the Taylor series for the linearization of the system.

For the design of controllers, it is necessary that the design requirements are satisfied. The following literary references were used as parameters of the project (Antonio, 2012), (Nicholas, 2015), (Ranieri, 2019), (Oguz Kose and Tugrul Oktay, 2019), thus specifying an overshoot of 20% with a rise time of 0.25 seconds. The simulation was developed in MATLAB/Simulink, where a controller based on gyroscopes (RollGyro, PitchGyro, YawGyro) and another controller based on angles (roll, pitch, yaw) were used for better stability.

In Figure 3, the control loop configuration for roll is shown, but it can be extended to pitch and yaw, as they all have the same control structure.

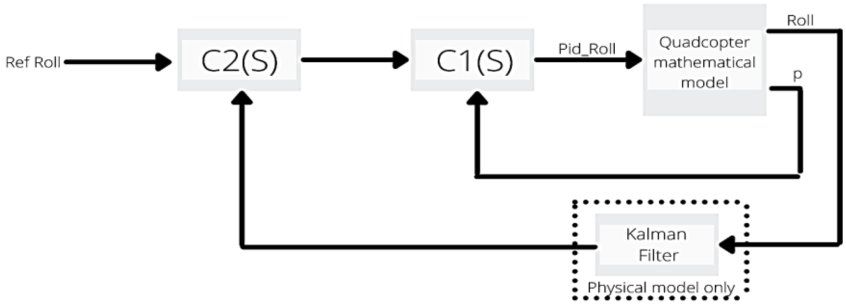

Figure 3. Quadcopter control law.

As it is a cascade control, the reference input goes through the first controller, C2 (turn controller), and then passes through a second controller, C1 (angle controller), where it sends the actuation command to the quadcopter . The data from sensors embedded in the UAV feedback into the mesh, and the attitude data also pass through a Kalman filter to eliminate noise. Calibration of the inertial sensors is also carried out when starting the vehicle.

With the control loops designed, the response of each controller and the command to increase or decrease the speed of the motors are added to the UAV equations, defined by the variable Throttle. According to the working configuration of the quadcopter, in this case "X", it is stipulated whether it is an addition or subtraction for the actuation commands. Motor equations are shown in Equations 11 through 14.

$$Motor_1 = \Omega_1 = \text{Throttle} + \text{Roll}_{\text{PID}} - \text{Pitch}_{\text{PID}} - \text{Yaw}_{\text{PID}} \tag{11}$$

$$Motor_2 = \Omega_2 = \text{Throttle} + \text{Roll}_{\text{PID}} + \text{Pitch}_{\text{PID}} + \text{Yaw}_{\text{PID}} \tag{12}$$

$$Motor_3 = \Omega_3 = \text{Throttle} - \text{Roll}_{\text{PID}} + \text{Pitch}_{\text{PID}} - \text{Yaw}_{\text{PID}} \tag{13}$$

$$Motor_4 = \Omega_4 = \text{Throttle} - \text{Roll}_{\text{PID}} - \text{Pitch}_{\text{PID}} + \text{Yaw}_{\text{PID}} \tag{14}$$

With the equations responsible for the motor speeds, the control is implemented in the microcontroller. As the motors work with a PWM (pulse-width modulation) signal, a gain (K) is used with the same parameters for the controllers and the motor signal. Figure 5 shows the transformation of the actuation command, coming from the controller, until its conversion into a PWM signal.

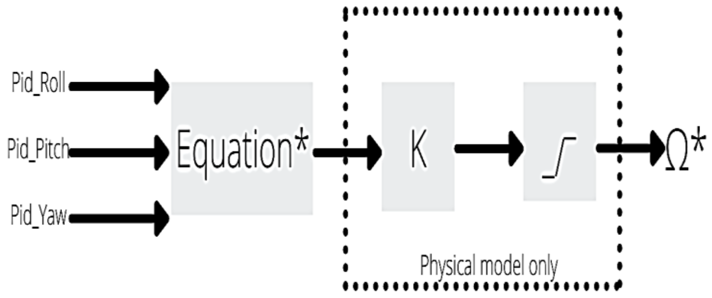

Figure 5. Speed control structure.

As can be seen in Figure 5, the dotted box represents the gain that allows the conversion of PID's signals into PWM, where a saturation that varies according to the used motor is also applied. In this way, the desired response from the motors is obtained according to the actuation command. The complete quadcopter system can be seen in the block diagram shown in Figure 6. The reference inputs feed the controller block that calculates the motor speeds.

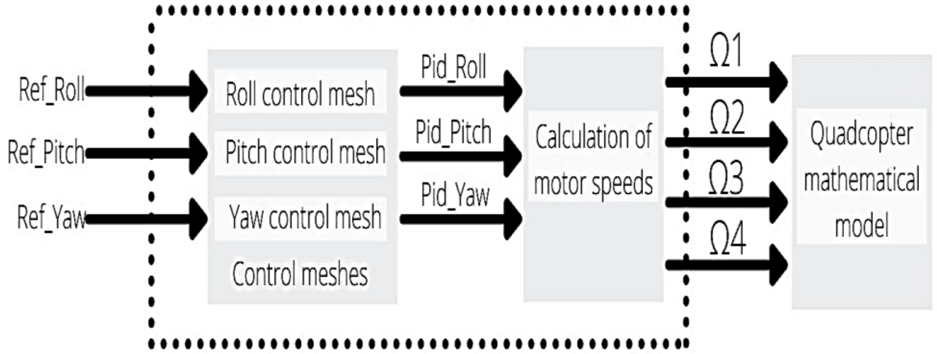

Figure 6. Complete system developed.

4. PHYSICAL SYSTEM STRUCTURE

The Atmega328P microcontroller was used, which is responsible for processing the signal, coming from the inertial sensor, being carried out using the Kalman filter. The inertial sensor used was an MPU10DOF, composed of a gyroscope, accelerometer and a BMP180 barometer with a compass. For signal transmission, APCv3220 antennas were used. The radio control used has data reception of 1 Km. All these informed sensors are of low cost. The communication protocol between the inertial sensor and the microcontroller was the I2C. Figure 7 shows the complete work scheme of the quadcopter.

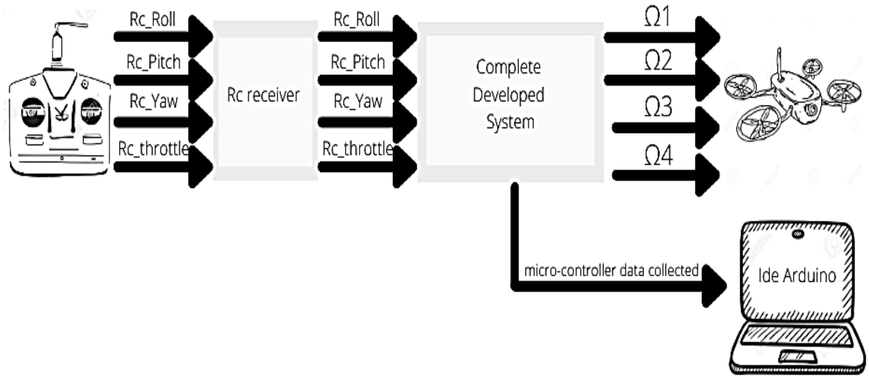

Figure 7. Complete work diagram.

As a way to improve the comparison of the results of the physical model, a Pixhawk was placed in the quadcopter to measure the attitude angles. Thus, it is possible to compare the responses of the inertial sensor of the UAV not only with the simulations in MATLAB/Simulink, but also with the IMU (Inertial Measurement Unit) of the Pixhawk. And in order not to overload the quadcopter's microcontroller, the readings from the Pixhawk were received using MATLAB.

For a better understanding of the work performed, the system developed on the test bench can be seen in Figure 8, consisting of two computers, one responsible for receiving data from the quadcopter and the other responsible for receiving data from the Pixhawk.

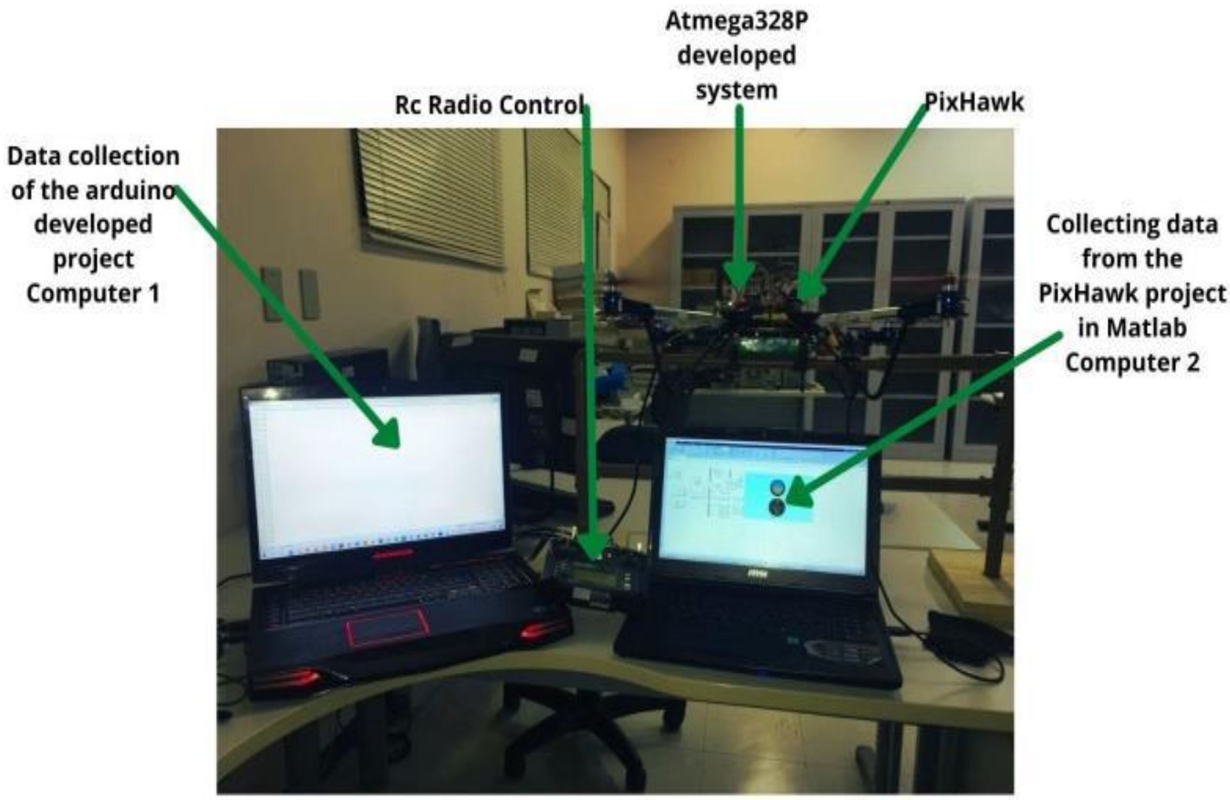

Figure 8. Complete developed physical system.

The two computers must be able to collect the data and thus compare the two systems, the developed system and the Pixhawk system. It can also be observed that there is a radio control. In this device, the type of signal being sent is PPM (Modulation Position Pulse), with each control signal being sent through a channel dedicated specifically to that signal. In the case of the physical system, these are the signals that act as a reference.

The controllers implemented in the microcontroller work with the data resulting from the Kalman Filter, which performs the filtering of the raw data from the inertial sensor (MPU10DOF).

The ESC (Electric Speed Controller) receives the PWM (pulse-width modulation) signals that come with data from the controllers, which are added to the speed that the operator needs to be able to perform quadcopter flights.

5. SIMULATION

In this section, the responses obtained in the simulation in MATLAB/Simulink will be presented and their performance analyzed. Also, the responses of the control loops embedded in the quadcopter will be presented. The Pixhawk's attitude measurement system was used for comparison with the quadcopter's attitude responses.

5.1 Results in MATLAB/Simulink simulation

The simulations were carried out using the mathematical model developed with the control loops designed in order to verify the behavior of the quadcopter in a simulation environment before leaving for the real world.

Figure 9 displays the controllers roll responses in a simulated environment for the 05°, 10°, 15° and 20° angles.

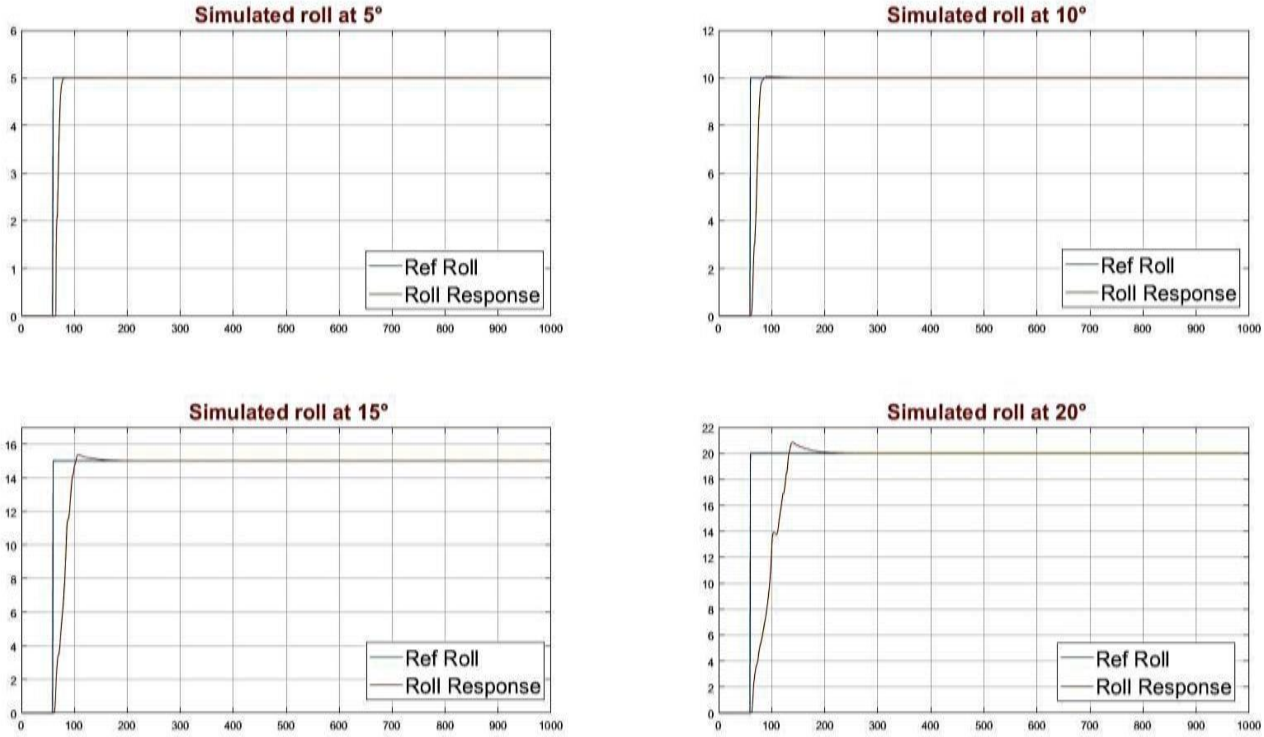

Figure 9. Roll response.

As can be seen in Figure 9, in the 20° roll response, the rise time is increasing a little more than expected, this is caused by the fact that the controllers were designed for small disturbances with small changes in angles.

In Figure 9 and Figure 10, the results obtained with the controllers designed for a maximum overshoot of 20% and a rise time of 0.25 seconds are presented. It can be verified that the responses obtained achieve the specified requirements.

The simulation responses for pitch are shown in Figure 10 for the 05°, 10°, 15°, and 20° angles.

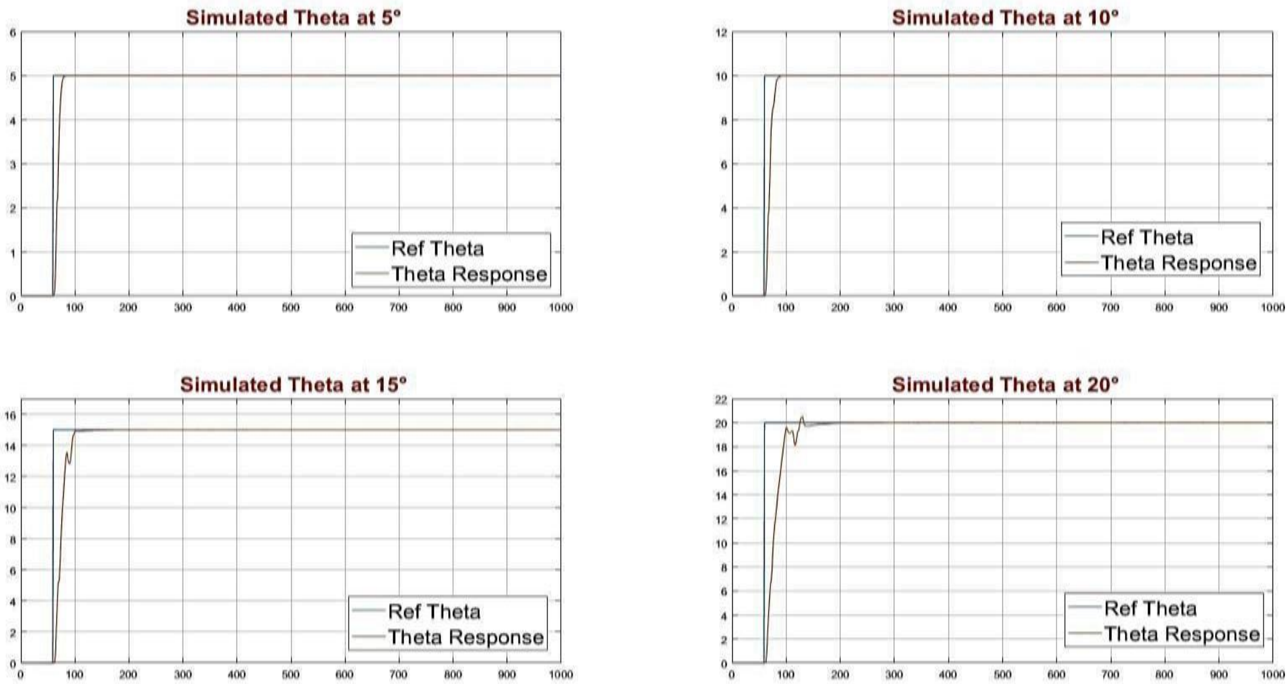

Figure 10. Pitch response.

5.2 Quadcopter Results

Once the response of the simulations came out as expected, the code with the controllers was loaded into the microcontroller embedded in the quadcopter.

In Figure 11, the roll responses for the quadcopter for the 05°, 10°, 15°, and 20° angles are shown.

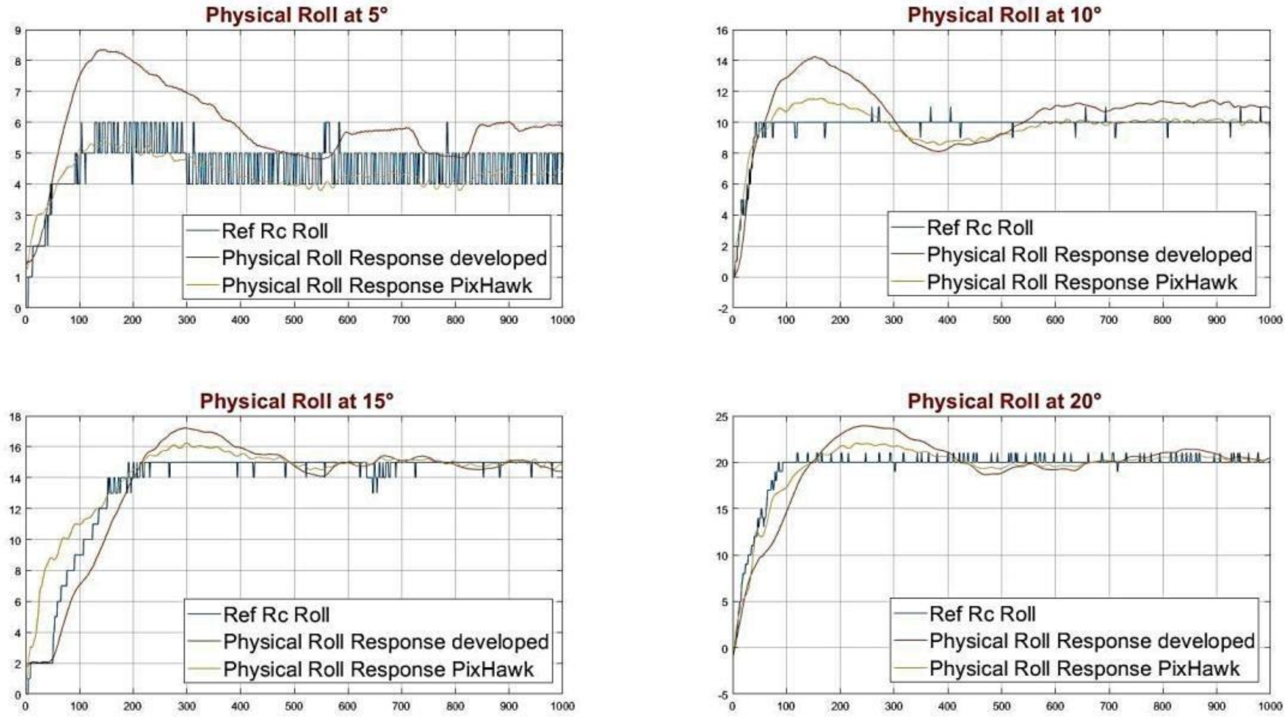

Figure 11. Roll response.

In Figure 12, the pitch responses for the quadcopter for the 05°, 10°, 15° and 20° angles are showed.

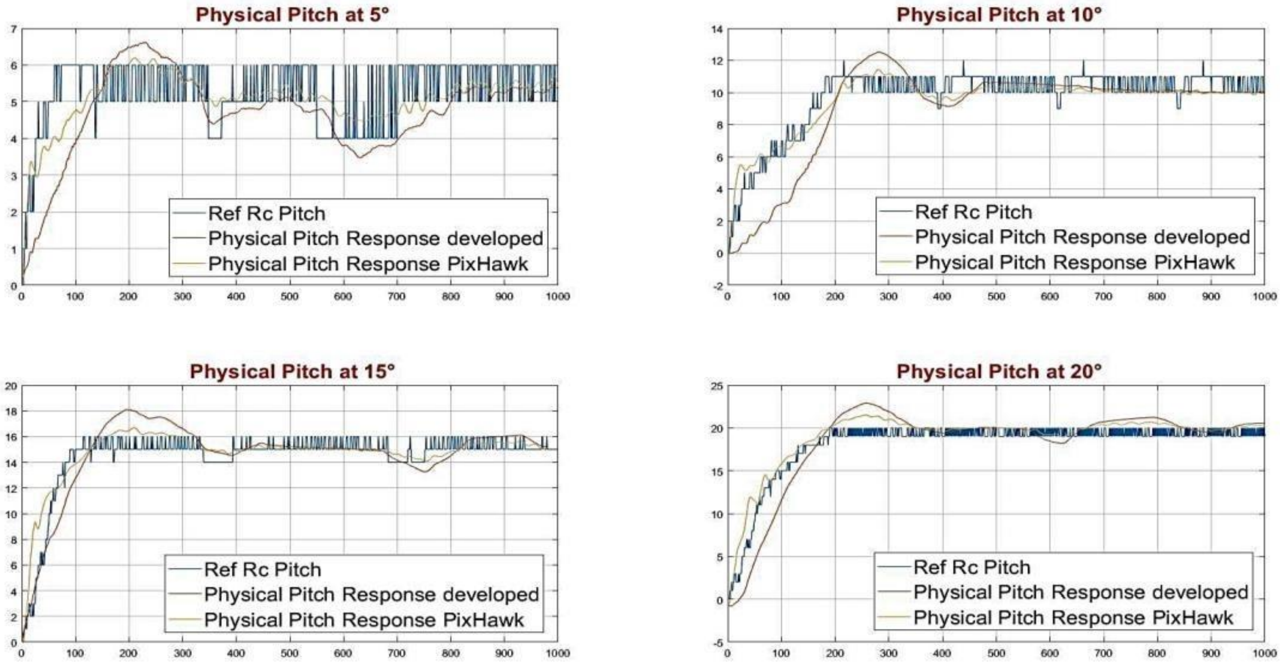

Figure 12. Pitch Response.

In Figures 11 and 12, the responses of the models in relation to the reference of the radio control are seen. In these figures, the radio control signals, the Pixhawk responses and the developed system are showed. Despite the responses of the system presented present an overshoot greater than that of the Pixhawk, even so, there is convergence to the desired reference value. The developed system and Pixhawk's are using the same gain values in their control loops.

It is worth paying attention to the fact that the radio control signal presents an oscillation of +/- 1 degree around the reference signal. This is due to the radio control being manually operated, so there is a human factor inaccuracy. Even with this oscillation, both the Pixhawk and the developed system are able to follow the reference signal.

Knowing the exact working times of the microcontroller, motor response, reading sensor data, filtering sensor data, reading PPM signals, radio control and the response time of stability drivers, such as responses of the entire physical system are even better. Even so, without this information, there is a good performance of the developed system, in relation to the Pixhawk system and the project requirements.

In Figure 13, the roll and pitch responses are shown, both for the simulation and for the model responses, for the angles of 05 °, 10 °, 15 ° and 20 °.

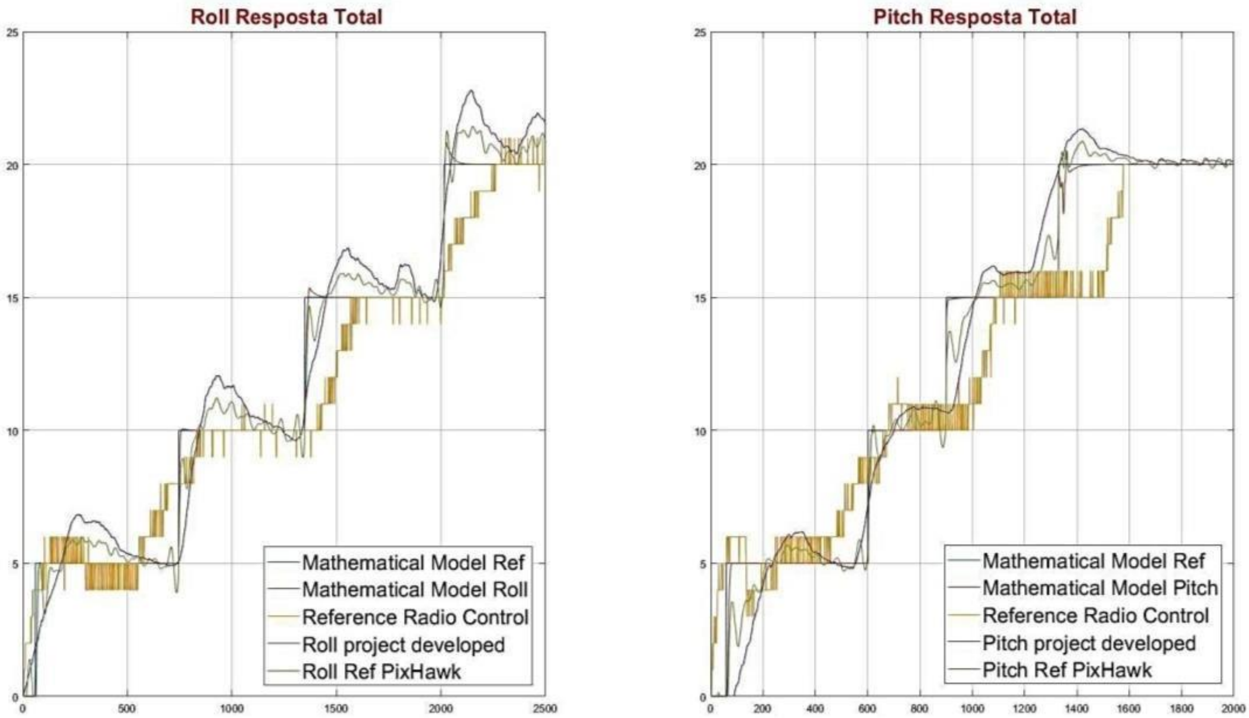

Figure 13. Comparison response.

As can be seen in Figure 13, the physical model behaved similar to the simulated one. The difference between the responses was small and occurs, as mentioned above, because the physical model shows the existence of noise and radio control delay, where there is a variation around 1 degree. Another problem is that some parameters used in the model were parameters obtained from the literature, which may be completely different from the parameters of the quadcopter in question.

6. CONCLUSIONS

According to the work developed, the controllers project managed to stabilize the quadcopter for the specified parameters. The differences between the Matlab/Simulink simulations and the quadcopter tests were small. The variations between the responses were due to the existence of noise, the delay in the use of radio control and because some parameters used in the physical model are parameters obtained from the literature. The results could be improved if a more computationally robust microcontroller were used, as it improves sensor readings by decreasing the delays caused by the data filtering algorithm. Another problem that could be solved is the variation in the reading of the radio control with the application of a filter, so that the reference signal would be more stable, as well as obtaining all the parameters of the quadcopter developed.

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