Design of a Robotic Bicopter

Özge Beyza Albayrak
Department of Mechanical Engineering, TED University
Kültür Mah. Ziya Gökalp Cd.
Ankara, Turkey
e-mail: obeyza.albayrak@tedu.edu.tr

Yağmur Ersan
Department of Mechanical Engineering, TED University
Kültür Mah. Ziya Gökalp Cd.
Ankara, Turkey
e-mail: yagmur.ersan@tedu.edu.tr

Ayşen Süheyla Bağbaşı
Department of Mechanical Engineering, TED University
Kültür Mah. Ziya Gökalp Cd.
Ankara, Turkey
e-mail: asuheyla.bagbasi@tedu.edu.tr

Ahmet Turgut Başaranoğlu
Department of Mechatronics Engineering, Atılım University
Kızılcaşar Mah. İncek
Ankara, Turkey
e-mail: turgutbasaranoglu@hotmail.com

Kutluk Bilge Arıkan
Department of Mechanical Engineering, TED University
Kültür Mah. Ziya Gökalp Cd.
Ankara, Turkey
e-mail: kutluk.arikan@tedu.edu.tr

***Abstract*—This article presents a Bicopter type of a flying robot with two rotary-wing units which are placed in a tandem form on the chassis. The rotors are tilted by the aid of the tilt mechanism. Cascaded type of PID controllers are designed on the dynamical models for the attitude and altitude dynamics. The simulated control systems are implemented and tuned on the Naze32 flight controller which is connected to a Raspberry Pi single board computer for real-time applications. The real-time performance is monitored and evaluated during the tests and it is seen that the system is suitable for indoor type of robotic applications.**

Keywords-flying robots; bicopter; flight testing; pid tuning

I. INTRODUCTION

In recent years, UAVs (Unmanned Aerial Vehicles) have been rapidly growing due to the technological changes and achievements in the industrial sectors [1]. Flying robots are widely used in defense industry, urban planning, telecommunication and even agriculture [2]. Therefore, there has been a significant increase in research on the development of the UAVs and flying robots. In addition to the mutual forms of multicopters such as quadcopters, hexacopters, and the octocopters, the Bicopter type of multicopters are studied, as well [1]. This type of flying robot has vertical take-off and landing by using two rotary-wing units which are placed in a tandem form on the chassis. The rotors are tilted by the aid of the tilt mechanism. The advantage of the Bicopter is the reduced number of motors and propellers which decreases the total cost, vibration, and the power demand [2].

This paper represents the design processes and the control of the Bicopter within the scope of the *ME 492 Senior Project* course in the Mechanical Engineering Department of TED University. The designed Bicopter is mainly manufactured by using aluminum beam as the frame and by aluminum sheet for the landing gear. Moreover, 3D printed parts are produced in order to build the tilt mechanism and carbon fiber plates are used to mount the system components. The altitude and attitude controller loops are developed and simulations are performed in order to achieve a stable flight. The cascaded type of PID controllers are designed according to the dynamics of the Bicopter. Although the mechanical design is similar to the one in [1], the control system and the utilized hardware are quite different. Simplified coupled models are utilized to design the cascaded type of PID controllers. Then, they are assessed on the detailed nonlinear model prior to the physical tests. In the first stage of the physical implementation, the attitude controllers are tested on a test bench. Finally, flight tests are performed while the altitude and attitude controllers are active.

II. MATHEMATICAL MODELING OF BICOPTER

A. Dynamical Modeling of the System

Mathematical model of the system plays a significant role for understanding the dynamics of the systems. The Bicopter

978-1-7281-3787-2/19/$31.00 ©2019 IEEE

consists of two propellers, two brushless motors, two servo DC motors and 3D printed tilt mechanisms in order to generate inclination for attitude control. In order to control the nonlinear system, its dynamical modeling is examined in detail. The Body Fixed (O $x_b y_b z_b$) and the Inertial (O$x_g y_g z_g$) Coordinate Systems are defined.

The thrust forces F_R and F_L are generated by the propellers and their components in x and z direction are shown in Fig. 1. Moreover, the inclination angles of the right and left hand side are denoted as λ_R and λ_L, respectively. Based on the rotation of the brushless motors, the drag moments, M_R and M_L are generated [5]. The sketch of the whole beam structure given below shows the generated moments by the thrust force components as well.

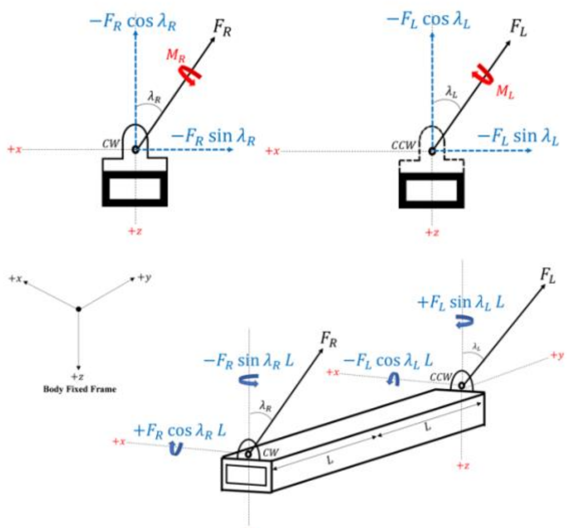

Figure 1. Forces & moments acting on the system.

In addition to that, the drag moment components are shown in Fig. 2. The direction of the drag moments are defined as in the opposite direction of the rotating brushless motors at the each end of the beam [7].

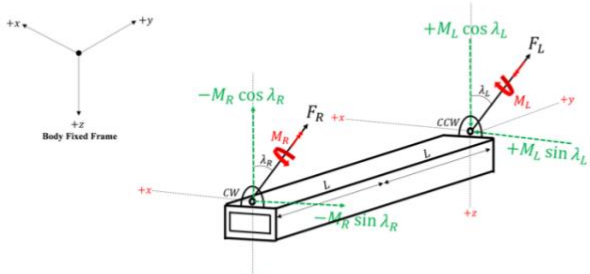

Figure 2. Drag moment components.

According the given free body diagrams above, by Newton's Second Law, the total force and moment equations in x, y and z directions are defined as given below;

$$\left.\begin{aligned} \Sigma F_x &= -F_R \sin\lambda_R - F_L \sin\lambda_L \\ \Sigma F_y &= 0 \\ \Sigma F_z &= -F_R \cos\lambda_R - F_L \cos\lambda_L \end{aligned}\right\} \quad (1)$$

$$\left\{\begin{aligned} \Sigma M_x &= F_L \cos\lambda_L L - F_R \cos\lambda_R L - M_R \sin\lambda_R + M_L \sin\lambda_L \\ \Sigma M_y &= -F_R \cos\lambda_R L - F_R \sin\lambda_R\, h + F_L \cos\lambda_L L + F_L \sin\lambda_L\, h \\ \Sigma M_z &= -F_L \sin\lambda_L L + F_R \sin\lambda_R L - M_R \cos\lambda_R + M_L \cos\lambda_L \end{aligned}\right. \quad (2)$$

B. *Equations of Motion*

The linear and angular motion dynamics of the Bicopter are derived according to chosen body and ground coordinate systems that defined earlier. The Euler angles, roll (ϕ), pitch (θ) and yaw (ψ) are defined and the 6DOF Euler Angles Aerospace Blockset in Simulink library is used to obtain the motion equations. The Euler rate vector matrix is determined as:

$$\begin{bmatrix}\dot\phi\\ \dot\theta\\ \dot\psi\end{bmatrix} = J\begin{bmatrix}p\\ q\\ r\end{bmatrix} = \begin{bmatrix}1 & (\sin\phi\tan\theta) & (\cos\phi\tan\theta)\\ 0 & \cos\phi & -\sin\phi\\ 0 & \sin\phi/\cos\theta & \cos\phi/\cos\theta\end{bmatrix}\begin{bmatrix}p\\ q\\ r\end{bmatrix} \quad (3)$$

By using the expression in Equation (3), the nonlinear model equations for both linear motion and angular motion of the system can be determined as in the following.

$$\left\{\begin{aligned} \ddot x &= -\frac{T_1}{m}(\sin\phi\sin\psi + \cos\phi\sin\theta\cos\psi) - \frac{\cos\theta\cos\psi}{m}T_3 \\ \ddot y &= -\frac{T_1}{m}(\sin\phi\cos\psi - \cos\phi\sin\theta\sin\psi) + \frac{\cos\theta\sin\psi}{m}T_3 \\ \ddot z &= -\frac{T_1}{m}(\cos\phi\cos\theta) - \frac{\sin\theta}{m}T_3 + g \\ \ddot\phi &= \frac{LT_2}{I_{XX}} \\ \ddot\theta &= \frac{hT_3}{I_{YY}} \\ \ddot\psi &= \frac{LT_4}{I_{ZZ}} \end{aligned}\right. \quad (4)$$

where

$T_1 = C_T({\omega_R}^2 \cos\lambda_R + {\omega_L}^2 \cos\lambda_L)$
$T_2 = C_T({\omega_R}^2 \cos\lambda_R - {\omega_L}^2 \cos\lambda_L)$
$T_3 = C_T({\omega_R}^2 \sin\lambda_R + {\omega_L}^2 \sin\lambda_L)$
$T_4 = C_T({\omega_R}^2 \sin\lambda_R - {\omega_L}^2 \sin\lambda_L)$

In the linear motion and angular motion equations, T_1, T_2, T_3 and T_4 are the thrust forces along different axis where C_T is the thrust coefficient of the propellers, which depends on the propeller characteristics, ω_R and ω_L are the rotational speed of the brushless motors, moreover, λ_R and λ_L are the tilt angles generated by the servo motors.

These nonlinear equations in Eq. (4) are simplified as given in Eq. (5) in order to build a simple model first to define the controller parameters for attitude and altitude control.

$$\left.\begin{aligned}\ddot{\phi} &= \frac{L\,C_T({\omega_R}^2 - {\omega_L}^2)}{I_{XX}}\\ \ddot{\theta} &= \frac{h\,C_T({\omega_R}^2 \sin\lambda_R + {\omega_L}^2 \sin\lambda_L)}{I_{YY}}\\ \ddot{\psi} &= \frac{L\,C_T({\omega_R}^2 \sin\lambda_R - {\omega_L}^2 \sin\lambda_L)}{I_{ZZ}}\\ \ddot{z} &= \frac{-C_T({\omega_R}^2 + {\omega_L}^2)}{m} + g\end{aligned}\right\} \tag{5}$$

The simplified versions of first three equations in Eq. (5), are used to build the attitude controllers, roll, pitch and yaw, respectively and the last expression is used to build the altitude controller. These four controller loops are embedded in Naze32 flight controller as in the form of 2DOF PID controller. Thus, the developed simulations are the representation of the actual flight controller card used in the physical system.

Physical parameters of the Bicopter are given in the following table, Tab. 1.

TABLE I. PHYSICAL PARAMETERS

Parameter	Physical Parameters of the Bicopter		
	Definition	***Value***	***Unit***
m	Mass of the System	1.192	kg
g	Gravitational Acceleration	9.81	m/s2
h	Vertical Distance Between CoG and Center of the Rotor	0.042	m
L	Horizontal Distance CoG and Rotor Center	0.225	m
C_T	Thrust Coefficient	0.1222	-
C_P	Power Coefficient	0.0797	-
C_Q	Torque Coefficent	0.0127	-
I_{XX}	The Moment of Inertia Along X Axis	0.116	kg.m2
I_{YY}	The Moment of Inertia Along Y Axis	0.0408	kg.m2
I_{ZZ}	The Moment of Inertia Along Z Axis	0.105	kg.m2

C. *Physical System*

The physical components and flight time calculations are defined for physical implementation. The designed Bicopter requires the following components: two brushless motors with propellers, ESCs, a LiPo battery, two servo motors, a Naze32 Flight Controller, Raspberry Pi 3 Model B+ for autonomous control and Pixy2 CMUcam5 image sensor for target detection and landing.

The propeller characteristics play a significant role while calculating the flight time of the robot. Therefore, based on the propeller diameter and its thrust and power coefficients, the required capacity of the battery is determined. The estimated flight time with two DJI 2212 920 KV brushless motors, 10" propellers and a 4S 4200 mAh LiPo battery is 8.4334 min. The constructed physical system of the Bicopter and its 3D modeling is shown in Fig. 3.

Figure 3. Designed bicopter & 3d modeling.

D. *Control Allocation*

The flight mechanism of the system provides the body motions of the Bicopter and the flight principles are given below in Fig. 4. The direction of the arrows give information about the rotational direction of the rotors and their size represents the rotational speed [4]. Moreover, the dashed round shapes indicates the position of the rotors parallel to the ground, where the rotors seat, therefore the inclination angle can be seen. In order to generate roll motion, motors are driven with different speeds. The pitch motion is generated by tilting the rotors in the same direction when the propellers are co-rotating. The yaw motion, on the other hand, is produced by tilting the rotors in the opposite direction while rotating both of them with the same speed. Finally, the vertical motion is generated by increasing or decreasing the motor speeds at the same time.

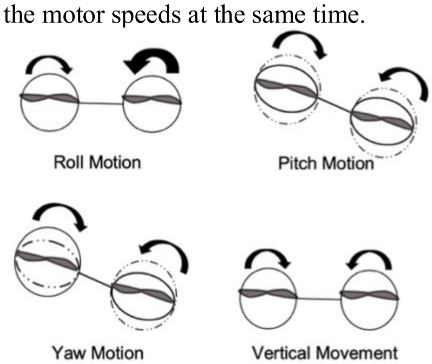

Figure 4. Motion mechanism of the bicopter.

III. CONTROLLER DESIGN

As mentioned earlier, the four different controller loops are developed by using the simplified versions of the nonlinear equations and controller parameters are defined accordingly. The obtained controller parameters are implemented to the nonlinear model and the simulation results are compared to each other to check the controllers' performance.

The nonlinear model consists of a mixer block, motor dynamics block, MATLAB function block which contains the force & moment equations defined in Eq. (1) & (2) and a 6DOF Aerospace Block Set which contains the robot's physical characteristics.

The mixer block outputs are denoted as motor duty ratios that specify the PWM inputs to the motor drivers, d1, d2, d3 and d4 and the relation between them is provided by using the controller outputs of the roll, pitch, yaw and altitude controllers c1, c2, c3 and c6, respectively. In the simplified model, the mixer block is developed by using summation blocks in Simulink and four main controller loops are coupled to each other.

The simplified models of four controller loops are given in Fig. 5 and Fig.6.

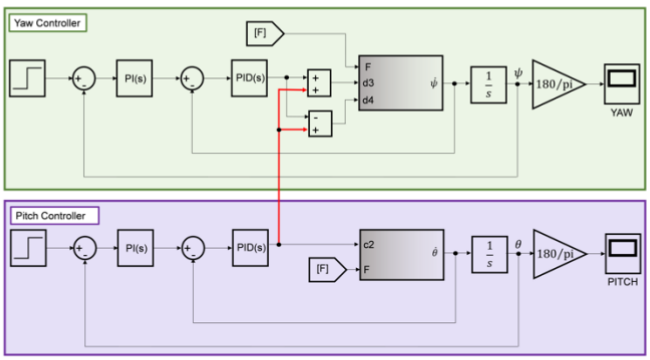

Figure 5. Yaw & pitch controller loops in simplified model.

Yaw - Pitch and Altitude - Roll controller loops are coupled to each other to represent the motor duty ratios.

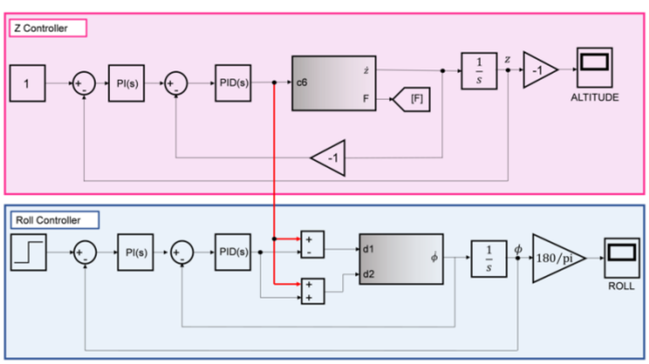

Figure 6. Altitude & roll controller loops in simplified model.

The system responses of roll, pitch, yaw and altitude controllers for both simplified and nonlinear models with the same controller parameters are shown in the following figures.

Under the step input, the roll controller response for both simplified and nonlinear model is given in Fig. 7. The overshoot and the steady state error is close to zero. Therefore, the response can be considered as ideal.

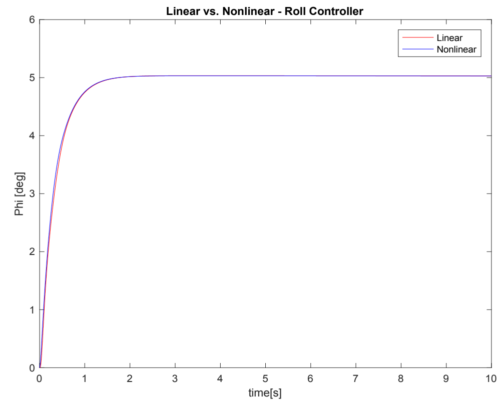

Figure 7. Roll controller simulation response.

The step response of the pitch controller is given in Fig. 8. The overshoot is 30% and settling time is approx. 8 seconds. However, the steady state error is close to zero since the pitch controller manages to hold the inclination angle at 5 degrees as given by the step input. Therefore, the cascaded type of PID controller works effectively.

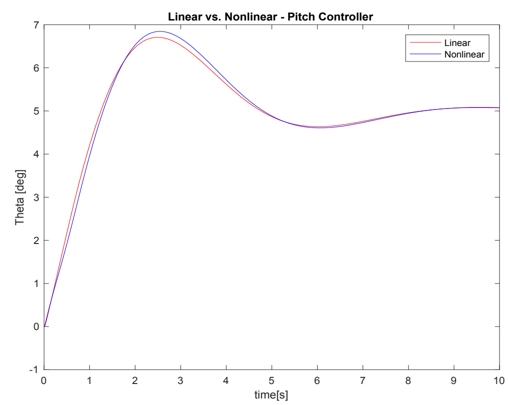

Figure 8. Pitch controller simulation response.

Yaw motion provides a movement around the system itself. The step response given below in Fig. 9, shows the yaw controller performance. The response time is short, and the overshoot is 4% and steady state error is close to zero.

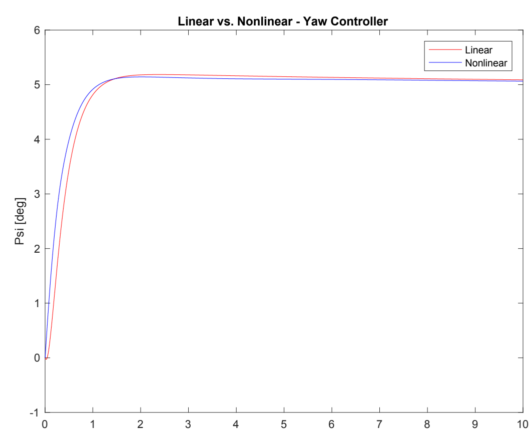

Figure 9. Yaw controller simulation response.

For the altitude control, the vertical movement is generated by increasing the height of the system. In Fig.10, the response shows that the altitude controller is able to hold the desired height of the Bicopter at a given value which is 1 meter.

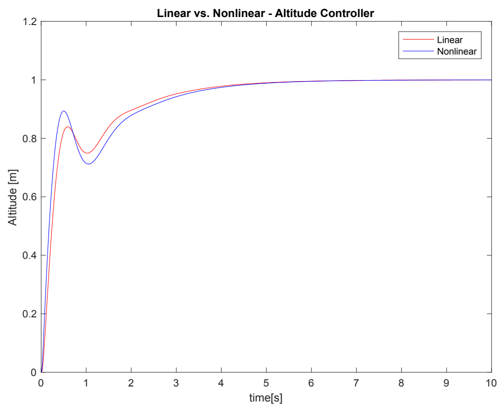

Figure 10. Altitude controller simulation response.

IV. PHYSICAL IMLEMENTATION

A. System Components

As mentioned previously, Naze32 flight controller and Raspberry Pi 3 Model B+ are the main components of our system. Before developing the autonomous control, a radio receiver is used which is connected to Naze32 flight controller to perform the necessary flight tests. Raspberry Pi is the required hardware for an autonomous flight. Therefore, when we use the RC system, Raspberry Pi pins are not used and Naze32 is connected to the Raspberry Pi with a USB cable only which transmits power from the LiPo battery to Naze32 [8].

B. Stabilization Testing & PID Tuning

When the Bicopter is completely assembled, some tests are required to understand the stabilization capabilities of our designed robot [6]. In Fig. 11, the test stand for the system is shown. The Bicopter is mounted to the aluminum plate and riveted to the ground, therefore the system is unstable [3].

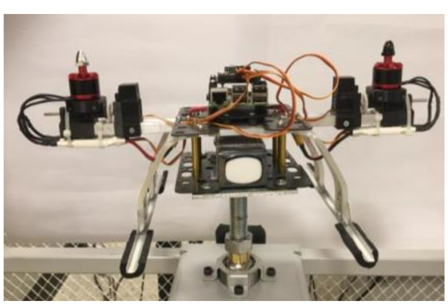

Figure 11. Bicopter test stand.

The controller parameters are tuned by using CleanFlight (CF) Configurator while performing the altitude & attitude tests, respectively.

C. Real-Time Implementation

After performing the flight tests and tuning the PID controller parameters to obtain a stable flight, Naze32 is connected to Raspberry Pi from the required pins and the motors are driven by using the Python code running from the Raspberry Pi terminal and by the developed Simulink model in order to perform the flight tasks autonomously. The connections between the Naze32 flight controller board and the Raspberry Pi 3B+ are shown in Fig. 12.

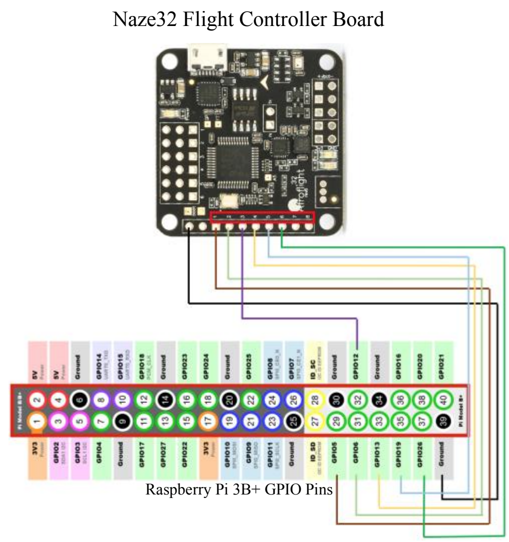

Figure 12. Naze32 – raspberry Pi Model B+ connections.

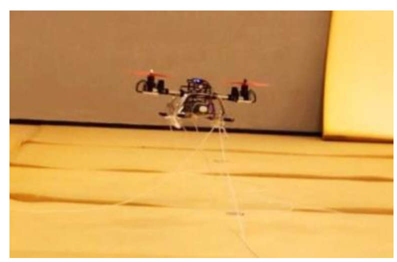

Figure 13. Flying bicopter from flight video.

V. CONCLUSION

This paper represents a two rotor flying robot whose dynamical system is able to tilt in order to perform various movements while the robot is flying. The developed Bicopter is constructed by defining the kinematics and kinetics of the system. Physical parameters are defined according to the detailed 3D modeling and system simulations are performed by using MATLAB & Simulink software to analyze the system response for improvement. In the simulations, attitude and altitude controller diagrams are built and cascaded type of PID controller gains are defined. Furthermore, the dynamical modeling and the defined physical parameters are combined to each other and the physical prototype of the system is built accordingly. The necessary system components are selected to perform the required flight tasks. Most importantly, in order to define attitude and altitude controllers gains of the flight configurator, the designed Bicopter is subjected to tests by adjusting the PID gains to obtain a sufficient flight. In simulations and flight tests, the system behaves smoothly and it is suitable for indoor applications such as swarm robotics.

ACKNOWLEDGMENT

We would like to express our sincere gratitude to Asst. Prof. Dr. K. B. A. for his constant support, encouragement and his precious supervision throughout our senior project. Also, we would like to thank A. T. B. for helpful and excellent assistance.

REFERENCES

[1] Q. Zhang, Z. Liu, J. Zhao, S. Zhang, “Modeling and Attitude Control of Bi-copter”. IEEE/CSAA International Conference on Aircraft Utility Systems, 2016, pp. 172-176.

[2] M. Nataraj, K. Madhukumar, M. Karthik, “Design and Fabrication of Two Rotors Bicopter,” IJRTER, vol. 3, no. 1, pp. 272-281, January 2017.

[3] Ø. Magnussen, “Multirotor Design Optimization: The Mechatronic Approach,” University of Agder. Unpublished Doctoral Thesis, May 2015.

[4] S. Salazar Cruz, A. Palomino, R. Lozano, “Trajectory tracking for a four rotor mini-aircraft,” IEEE Decision and Control and the European Control Conference on Aircraft Utility Systems, 2005, pp. 2505-2510.

[5] N. Zlatanov, “Multi Rotor Aircraft Dynamics, Simulation and Control,” Technical Report, August 2016.

[6] G. M. Hoffmann, H. Huang, S. L. Waslander, and C. J. Tomlin, “Quadrotor helicopter flight dynamics and control: Theory and experiment,” Proceedings of the AIAA Guidance, Navigation and Control Conference and Exhibit, Aug. 2007.

[7] H. Huang, G. M. Hoffmann, S. L. Waslander, and C. J. Tomlin, “Aerodynamics and control of autonomous quadrotor helicopters in aggressive maneuvering,” IEEE International Conference on Robotics and Automation, pp. 3277–3282, May 2009.

[8] P. Castillo, R. Lozano, and A. Dzul, “Stabilization of a mini rotorcraft with four rotors,” IEEE Control Systems Magazine, pp. 45–55, Dec. 2005.