



Sliding Mode Control-Based Modeling and Simulation of a Quadcopter

Rahmi Elagib ^{a*} and Ahmet Karaarslan ^a

^a Department of Electrical and Electronics Engineering, Ankara Yildirim Beyazit University, Ankara, Turkey.

Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

This article discusses the use of Sliding Mode Control (SMC) for the control of a four-rotor vertical take-off and landing (VTOL) unmanned aerial vehicle (UAV). The Newton-Euler method is utilized to build the quadcopter's dynamic model. The model is divided into under-actuated and fully actuated subsystems. Even though controlling UAVs is difficult owing to their extremely nonlinear characteristics, previous experimental trials and simulation studies have proved that the sliding mode controller yields satisfactory performance and disturbance tolerance. The contribution of this study is the presenting of an accurate quadcopter modeling and simulation employing a sliding mode controller and a Newton-Euler formula to reduce chattering. In this study, SMC was used to control the altitude and attitude of the quadcopter. MATLAB/Simulink was used to show the quadcopter dynamic model and controller model, and the result illustrating the controller's performance in different conditions was acquired.

Keywords: Quadcopter; Unmanned air vehicle; VTOL; MATLAB/Simulink; SMC.

*Corresponding author: Email: rahmielagib@gmail.com, rahmyelageeb@gmail.com;

1. INTRODUCTION

In recent years, quadcopters, or unmanned aircraft with four rotors have been the focus of UAV research. Although quadcopter control is difficult because of its nonlinear, instability, and vulnerability to external disturbances, building control systems for quadcopters is a growing field of study. Researchers have examined a variety of approaches for manipulating the motion of quadcopters. Sliding mode control (SMC) is a robust and efficient nonlinear control system that may be used in uncertain environments.

SMC consists of two components: a discontinuous control law that drives the error vector toward a decision rule known as the sliding surface. Second, after the error vector is restricted to the sliding surface, a continuous component of the controller acts to follow the dynamics enforced by the equations characterizing the sliding surface. SMC in quadcopters has been the subject of several investigations, including publications [1-7]. D.A. Santos & J.A. Ricardo Jr [8] investigated a smooth second-order SMC for a hexacopter for position and attitude control issues. Yao et al. [9] provided an integral first-order SMC, but to eliminate the high frequency control, it employed an arctangent approximation of the discontinuities.

Because of its drawbacks, such as chattering and computational time, SMC is often used in conjunction with other controllers to control the quadcopters. The attitude and attitude of quadcopters have been controlled by researchers using a variety of control strategies that combine SMC with other methods including LQR, fuzzy logic, backstepping, etc. Bensalah et al. [10] the use of Image-Based Visual Servoing (IBVS) to control a UAV is described. The SMC employs an approximation dynamic in the control model, and uncertainties in all control model parameters are investigated. Although the obtained simulation results demonstrate the suggested controller's effectiveness in tracking the produced trajectories, it fails to eliminate the chattering effect by utilizing a smooth sign function or sliding mode control with a higher order. In terms of the picture plane inaccuracy, the model fails to combine sensor data with optical flow from image information to accurately estimate Quadrotor motions. Even though the quadcopter is subject to external disturbances, little attention has been paid to this problem in

designing an SMC controller for the vehicle in several studies. Matouk et al. [11] proposed a MATLAB/Simulink-based second-order sliding mode control (2-SMC) for controlling a quadcopter. Using this strategy, it was possible to develop very stable control laws for each position and attitude state. The design did not address the external disturbances, and the system was not tested experimentally. Noordin et al. [12] developed a sliding mode control to keep a quadrotor's altitude and orientation stable in the presence of external disturbances. External disturbances were mostly ignored in the research, which studied an "X-configuration quadcopter" and considered saturation function.

Dikmen et al. [13] used Ant Colony Optimization (ACO), Invasive Weed Optimization (IWO), and Firefly Optimization (FO) methods to obtain optimal Sliding Mode Controller (SMC) parameters for attitude and position control of quadcopter. The improved SMC parameters yield good results. The significant disadvantage of this study is that the algorithm requires a lot of processing power, especially in the case of FA. Higher-Order Sliding Mode Control (HOSMC) based on a super-twisting algorithm for quadcopter control was developed by Mebaye [14]. Lagrange formalism was used to derive the mathematical model which includes aerodynamic effects and gyroscopic moments.

This paper shows quadrotor attitude stabilization and attitude stabilization in MATLAB/Simulink using an SMC controller. Nonlinearity, parameter uncertainty, and external disturbances were considered in the development of the quadrotor control system. This study is noteworthy since it was able to control and maintain the attitude of a quadcopter while accounting for external disturbances caused by quadcopter components like batteries and sensors. This work has the following components: Section II of A Quadcopter Newton-Euler Formula in Dynamic. Section III covered sliding mode control. Section IV describes the development process of the SMC. Section V tests the whole model, including the SMC controller, using MATLAB/Simulink. The analysis and results are very certainly included in section VI of the research.

2. QUADCOPTER WORKING PRINCIPLE AND DYNAMIC MODEL

Despite having 6 degrees of freedom (6-DOF), the quadcopter is an under-actuated aircraft. The vehicle features four propellers positioned

orthogonally. Vehicle balance and motion are ensured by separate manipulation of propeller speed and direction. One set of rotors spins clockwise, while the other pair turns counterclockwise to keep the system stable. The quadcopter can go forward, backward, and sideways by varying the speed of the rotors. Altitude, Pitch, Roll, and Yaw are the 4 different types of quadcopter motion based on the relative motion of the four propellers.

Quadcopters can be maneuvered up and down by increasing or lowering the speed of all four propellers using the throttle. Quadcopters descend when all propellers are running at slow speeds. However, the vehicle hovers when the four propellers spin faster. The quadcopter's longitudinal axis rotation generates the roll angle. The vehicle accelerates to the left side direction while the two propellers on the right side are spinning at an increasing speed. When the two propellers on the left side of the vehicle are spinning fast, the vehicle moves in the right-side direction. Pitch is the term used to describe the quadcopter's ability to rotate around a side axis (either forward or backward). The rotation occurs when the vehicle's front propellers are spinning at a high speed. The quadcopter's vertical axis is rotated using the yaw control (either to the left or to the right). The quadcopter rotates counterclockwise when two of its left-side propellers spin fast.

The vehicle accomplishes a counterclockwise rotation when its right-side propellers spin fast. Roll, pitch, yaw, and angular velocities may be determined using an Earth-fixed Frame(E), while the linear acceleration is determined using a Body-fixed Frame(B). The X-configuration with B and E frames is shown in **Fig. 1** Three translational states (x, y, z), three rotational states (ϕ, θ, ψ), and their derivatives ($\dot{x}, \dot{y}, \dot{z}, \dot{\phi}, \dot{\theta}, \dot{\psi}$).

Where, $x, y,$ and z are the position in the $x, y,$ and z axes, $\dot{x}, \dot{y},$ and \dot{z} are the angular velocities, ϕ, θ, ψ are the roll, pitch, and yaw angles, and the parameters, $\dot{\phi}, \dot{\theta},$ and $\dot{\psi}$ are the speed for roll, pitch, and yaw respectively. The quadrotor dynamics were expressed using Newton-Euler translational and rotational dynamics formulation Ferry [15] as:

$$\ddot{x} = \frac{1}{m} ((\sin \psi \sin \phi - \cos \psi \sin \theta \sin \phi)U_1 - A_x \dot{x}) \quad (1)$$

$$\ddot{y} = \frac{1}{m} ((\cos \psi \sin \phi + \sin \psi \sin \theta \cos \phi)U_1 - A_y \dot{y}) \quad (2)$$

$$\ddot{z} = g - \frac{1}{m} (\cos \psi \cos \phi U_1 - A_z \dot{z}) \quad (3)$$

$$\ddot{\phi} = \left(\frac{I_{yy} - I_{zz}}{I_{xx}} \right) \dot{\psi} \dot{\theta} + \left(\frac{J_r \Omega_r}{I_{xx}} \right) \dot{\theta} + \left(\frac{1}{I_{xx}} \right) U_2 - \frac{A_\phi \dot{\phi}}{I_{xx}} \quad (4)$$

$$\ddot{\theta} = \left(\frac{I_{zz} - I_{xx}}{I_{yy}} \right) \dot{\psi} \dot{\phi} - \left(\frac{J_r \Omega_r}{I_{yy}} \right) \dot{\phi} + \left(\frac{1}{I_{yy}} \right) U_3 - \frac{A_\theta \dot{\theta}}{I_{yy}} \quad (5)$$

$$\ddot{\psi} = \left(\frac{I_{xx} - I_{yy}}{I_{zz}} \right) \dot{\theta} \dot{\phi} + \left(\frac{1}{I_{zz}} \right) U_4 - \frac{A_\psi \dot{\psi}}{I_{zz}} \quad (6)$$

The input signal U_1 is the total thrust of the 4 rotors. And U_2, U_3 and U_4 are the moments for pitch, roll, and yaw respectively. Where m represents the mass of the quadrotor, J_r is the inertia of the rotor, and $I_{xx}, I_{yy},$ and I_{zz} are the inertia of the quadrotor in $x, y,$ and z respectively. The inputs can be given by:

$$U_1 = b(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2) \quad (7)$$

$$U_2 = b \sin \left(\frac{p_i}{4} \right) (\Omega_1^2 - \Omega_2^2 - \Omega_3^2 + \Omega_4^2) \quad (8)$$

$$U_3 = b \sin \left(\frac{p_i}{4} \right) (\Omega_1^2 + \Omega_2^2 - \Omega_3^2 - \Omega_4^2) \quad (9)$$

$$U_4 = d(\Omega_1^2 + \Omega_3^2 - \Omega_2^2 - \Omega_4^2) \quad (10)$$

$$\Omega_r = \Omega_1^2 - \Omega_2^2 + \Omega_3^2 - \Omega_4^2 \quad (11)$$

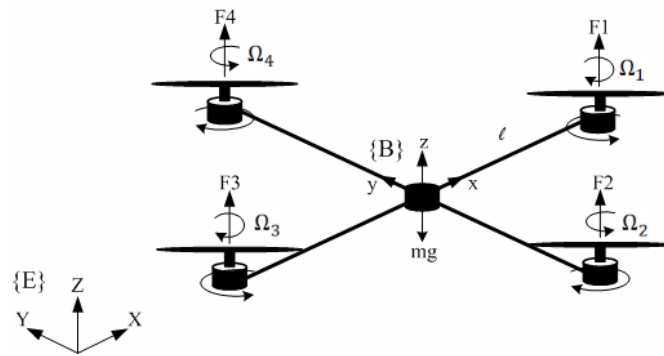


Fig. 1. Quadcopter UAV configuration

Where b is thrust coefficient, and d is drag coefficient, the angular speed for each rotor is $\Omega_1, \Omega_2, \Omega_3, \Omega_4$. Ω_r is the general angular speed.

3. SLIDING MODE CONTROLLER

Sliding Mode Control is a procedure that is evolved from Variable Structure Control (VSC). Slide mode control aims to limit the amount of error in the system. **Fig. 2** illustrates the SMC law U_x **Eqn.23.**, which has two key components: a continuous part (equivalent control U_{eqX}) and a discontinuous part (switching control \hat{U}_x). The switching control rule directs the system to the user-specified sliding surface, S , and maintains the system's trajectory on this surface throughout switching control rule. The equivalent control is used to guarantee that the system state goes toward the sliding surface. In attempt to develop a sliding surface or decision rule, the error must be defined. To put it another way, an error is a difference between a value's actual value and the value desired.

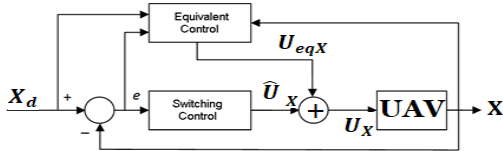


Fig. 2. Sliding-mode control for a quadcopter

$$e_x = X_d - X \quad (12)$$

By calculating the error's first and second derivatives:

$$\dot{e}_x = \dot{X}_d - \dot{X} \Rightarrow \ddot{e}_x = \ddot{X}_d - \ddot{X} \quad (13)$$

The sliding surface is given according to the following equation:

$$S_x = \dot{e}_x + \lambda_x e_x \quad (14)$$

Also, the first derivative can be computing as:

$$\dot{S}_x = \ddot{e}_x + \lambda_x \dot{e}_x \quad (15)$$

Where variable e_x is the tracking error, and variable λ_x is the tuning parameter must satisfy the condition ($\lambda_x > 0$), S_x is sliding surface $S_x = 0$, X is state space.

To design the control law, a Lyapunov function $V(S_x)$ is defined. This function must be positive-definite.

3.1 Stability Analysis

A Lyapunov function is defined as:

$$V(S_x) = \frac{1}{2} S_x^2, (X=z, \phi, \theta, \psi) \quad (16)$$

Derivation of (16) gives:

$$\dot{V}(S_x) = S_x \dot{S}_x$$

then the desired sliding condition is verified and

Lyapunov stability is guaranteed. The chosen law for the attractive surface must satisfy

$$S_x \dot{S}_x = -k_{x1} S_x - k_{x2} \text{sign}(S_x) < 0 \quad (17)$$

As mentioned, the control law, U_x , consists of two parts: a continuous part, U_{eqX} and a discontinuous part, \hat{U}_x .

$$U_x = \hat{U}_x + U_{eqX} \quad (18)$$

$$\hat{U}_x = -k_{x1} S_x - k_{x2} \text{sign}(S_x) \quad (19)$$

Where k_{x1}, k_{x2} are the tuning parameters, sign can be as:

$$\text{sign}(S_x) = \begin{cases} +1 & \text{if } S_x > 0 \\ -1 & \text{if } S_x < 0 \end{cases} \quad (20)$$

4. QUADCOPTER SMC CONTROLLER

A sliding mode control (SMC) is used in this investigation to obtain the desired altitude and attitude. The proposed control law is developed by dividing the system model into two subsystems, a **fully actuated subsystem**, and a **under-actuated subsystem**, as shown in **Fig. 3**. Unlike in the under-actuated subsystem, where the inputs U_2 and U_3 are smaller than the number of outputs (x, y, ϕ, θ), in the fully actuated subsystem there are two outputs (z, ψ) for each of the inputs (U_1, U_4).

4.1 Under-Actuated Subsystem Control

It was decided to separate the control of the under-actuated subsystem into two separate blocks in the design, an inner-loop, and an outer loop. Using the correction control block (the outer loop), the desired altitude can be obtained by converging the error and extracting the desired attitude angles θ_d and ϕ_d from x and y . In order to achieve roll and pitch control an SMC controller is employed as the inner-loop controller to drive the attitude angles and from the outer-loop controller.

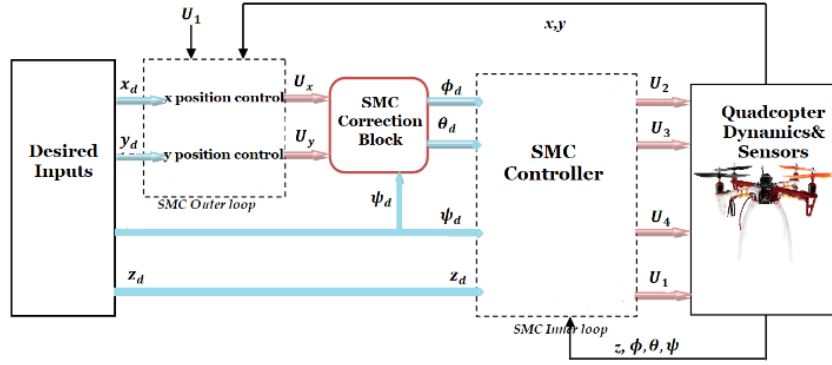


Fig. 3. UAV control system block diagram

Using **Eqn.1.,2.** the following x, y position equation may be derived:

$$U_x = (\cos\phi_d \sin\theta_d \cos\psi - \sin\phi_d \sin\psi) \quad (21)$$

$$U_y = (\cos\phi_d \sin\theta_d \sin\psi - \sin\phi_d \cos\psi) \quad (22)$$

$$\begin{bmatrix} U_x \\ U_y \end{bmatrix} = \begin{bmatrix} \sin\psi & -\cos\psi \\ \cos\psi & \sin\psi \end{bmatrix} \begin{bmatrix} \cos\phi_d \sin\theta_d \\ \sin\theta_d \end{bmatrix} \quad (23)$$

$$\begin{bmatrix} \cos\phi_d \sin\theta_d \\ \sin\theta_d \end{bmatrix} = \begin{bmatrix} \sin\psi & -\cos\psi \\ \cos\psi & \sin\psi \end{bmatrix}^{-1} \begin{bmatrix} U_x \\ U_y \end{bmatrix} \quad (24)$$

By starting from the second row ϕ_d and then θ_d can be calculated as follows:

$$\begin{bmatrix} \phi_d \\ \theta_d \end{bmatrix} = \begin{bmatrix} \arcsin(U_x \sin\psi - U_y \cos\psi) \\ \arcsin((U_x \cos\psi - U_y \sin\psi) / \cos\phi_d) \end{bmatrix} \quad (25)$$

4.2 Fully Actuated Subsystem Control

The objective of this fully actuated subsystem controller is to minimize the error in the altitude and yaw angle e_z and e_ψ to satisfy the following conditions:

Deriving **SMC controller for altitude:**

By applying **Eqn.17. , 18. , 19. , 20.:**

$$e_z = z_d - z = 0 \Rightarrow \dot{e}_z = \dot{z}_d - \dot{z} \Rightarrow \ddot{e}_z = \ddot{z}_d - \ddot{z} \quad (25)$$

$$S_z = \dot{e}_z + \lambda_z e_z \Rightarrow \dot{S}_z = \ddot{e}_z + \lambda_z \dot{e}_z \quad (26)$$

by substituting **Eqn.25, 26.** sliding condition $\dot{S}_z=0$ result is obtained.

$$\dot{S}_z = (\ddot{z}_d - \ddot{z}) + (\dot{z}_d - \dot{z})\lambda_z = 0 \quad (27)$$

$$\dot{S}_z = \left(\ddot{z}_d - g + \frac{1}{m} (\cos\psi \cos\phi U_1 + A_y \dot{y}) \right) + (\dot{z}_d - \dot{z})\lambda_z \quad (28)$$

Since the system is in a sliding condition and $U_z = U_{eqz}$, $A_y \dot{y} = 0$ are considered, **Eqn.28** can be derived:

$$\dot{S}_z = \left(\ddot{z}_d - g + \frac{U_{eqz}}{m} (\cos\psi \cos\phi) \right) + \lambda_z (\dot{z}_d - \dot{z}) \quad (29)$$

The control laws for the altitude and yaw angle can be derived using classical SMC theory:

$$U_{eqz} = \left(\frac{m}{\cos\phi \cos\theta} \right) (\ddot{z}_d - g + \lambda_z (\dot{z}_d - \dot{z})) \quad (30)$$

From **Eqn.23, 24:**

$$U_1 = U_z = \hat{U}_z + U_{eqz}, \hat{U}_z = -k_{z1} S_z - k_{z2} \text{sign}(S_z) \quad (31)$$

$$U_1 = \left(\frac{m}{\cos\phi \cos\theta} \right) (g - \ddot{z}_d - \lambda_z \dot{e}_z) + k_{z1} S_z + k_{z2} \text{sign}(S_z) \quad (32)$$

The same approach used to derive altitude may also be used to derive SMC for roll, pitch, yaw, x , and y as illustrated below:

$$U_x = \frac{m}{U_1} (\ddot{x}_d - \lambda_x e_x) + k_{x1} S_x - k_{x2} \text{sign}(S_x) \quad (33)$$

$$U_y = \frac{m}{U_1} (\ddot{y}_d - \lambda_y e_y) + k_{y1} S_y - k_{y2} \text{sign}(S_y) \quad (33)$$

$$U_2 = \frac{l_{xx}}{I} \left(\ddot{\phi}_d - \frac{l_{zz} - l_{xx}}{l_{yy}} \dot{\theta} \dot{\phi} + \lambda_\phi \dot{e}_\phi \right) + k_{\phi 1} S_\phi + k_{\phi 2} \text{sign}(S_\phi) \quad (34)$$

$$U_3 = \frac{l_{yy}}{I} \left(\ddot{\theta}_d - \frac{l_{zz} - l_{xx}}{l_{yy}} \dot{\theta} \dot{\phi} + \lambda_\theta \dot{e}_\theta \right) + k_{\theta 1} S_\theta + k_{\theta 2} \text{sign}(S_\theta) \quad (35)$$

$$U_4 = l_{zz} \left(\ddot{\psi}_d - \frac{l_{zz} - l_{xx}}{l_{yy}} \dot{\theta} \dot{\phi} + \lambda_\psi \dot{e}_\psi \right) + k_{\psi 1} S_\psi + k_{\psi 2} \text{sign}(S_\psi) \quad (36)$$

5. RESULTS AND DISCUSSION

To verify the performance of the proposed controller, a MATLAB/Simulink is presented in this section. The parameters of the quadrotor used in the simulation are selected in Table 1.

The suggested SMC approach's design parameters have been tuned manually in

MATLAB/Simulink in order to track the trajectory smoothly. Table 2. list the parameters of the recommended controllers.

Figures. from 4 to 7 show the actual and desired.

Values of altitude, roll, pitch, and yaw.

Table 1. Shows the parameters of the quadcopter

Parameter	Symbol	Value
Quad. mass	m	0.984 kg
Arm length	l	0.225m
Gravity	g	9.81 m/s ²
Rotor inertia	J _r	2.6e-06 kg.m ²
Inertia constants	I _{yy} , I _{xx}	9.5*10 ⁻³ kg.m ²
	I _{zz}	1.86*10 ⁻² kg.m ²
Thrust Coeff.	b	1.4865e-07N.s ²
Drag coeffi.	d	2.925e-09 N.m.s ²
Aerodynamic coefficient	A _φ ,A _θ ,A _ψ	0 N/rad/s
Air Drag coeffi.	A _x ,A _y ,A _z	0 N/m/s

Table 2. shows SMC design parameters tuning

Tuning	Controller	SMC			
		Roll	Pitch	Yaw	Altitude
k _{X1}		1.97	1.97	1	16.33
k _{X2}		1.81	1.81	0	14.1
λ _X		3.68	3.68	18	2.5

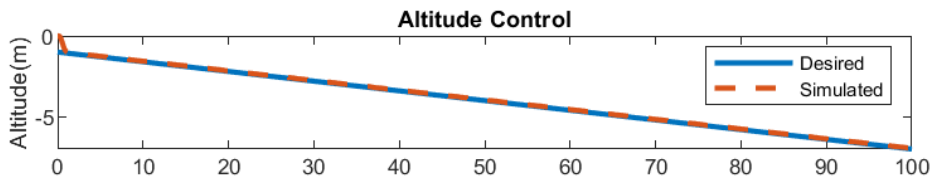


Fig. 4. Shows the actual and desired altitude values

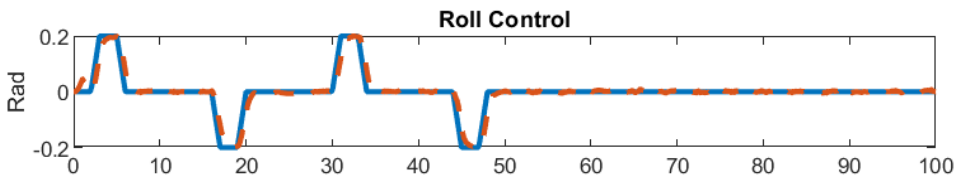


Fig. 5. Shows the actual and desired roll values

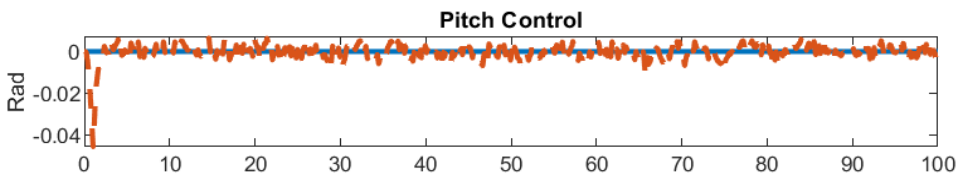


Fig. 6. Shows the actual and desired pitch values

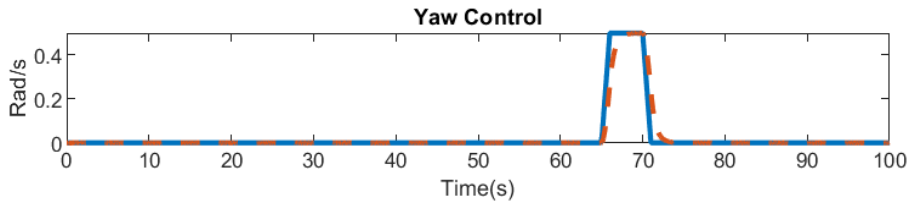


Fig. 7. Shows the actual and desired yaw values

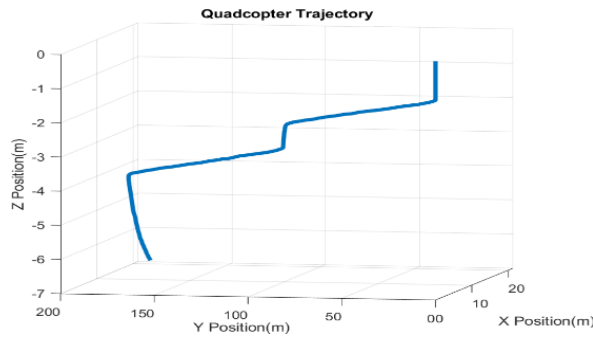


Fig. 8. Quadcopter trajectory

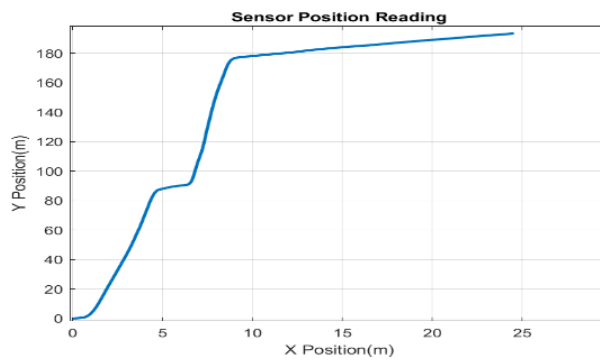


Fig. 9. Sensor position reading

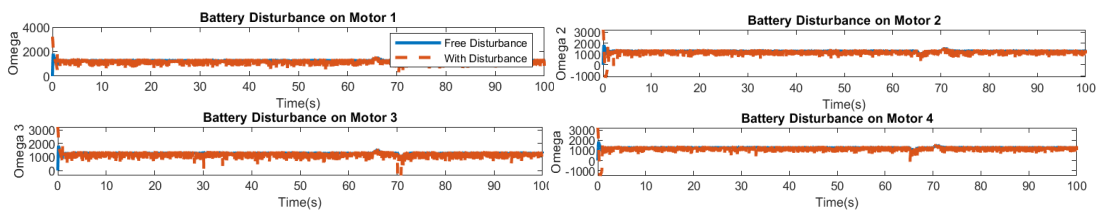


Fig. 10. Angular speed vs actual angular speed with battery disturbances included

Fig. 4 illustrates the desired altitude and the actual values. Maintaining the desired altitude was not affected by any noticeable disturbance. And the disturbances were kept to a minimum. Roll actual and desired values are shown in Fig. 5. With a rise time of 202.724 ms and an overshoot percentage of 120.852 %, the controller was able to control the roll angle. Fig. 6 shows the desired and actual pitch angle values. The pitch angle was achieved, although the controller

recorded some disturbances. Yaw desired and actual value was shown in Fig. 7. With rise time of 792 ms and an overshoot percentage of 0.505 %, the controller was able to follow the trajectory with neglectable disturbances. And the controller, on the other hand, has kept yaw angles stable throughout the flight. A 3D trajectory was provided in Fig. 8, the figure depicts the overall system performance (the quadcopter with sensors and controls). The quadcopter's X, Y,

and Z axes were exhibited. The vehicle's position was controlled by the controller, and a satisfactory trajectory was obtained. Fig. 9 the gyroscope sensor's X and Y position readings are shown. According to the findings, the sensor was able to accurately measure x and y.

Fig. 11 depicts the motors' speeds. As shown, the motors spin at roughly 12000 rpm, which was successfully maintained and controlled.

Simulating the spinning of the motors included considerations for battery and external

disturbance. Fig. 12 shows a speed of the motor (RPM) disturbances. Time periods 60, 66, and 70.2 s all have been effected by disturbances.

Fig. 13 shows the angular speeds of all four motors. However, these impacts are insignificant in comparison to the controller as a whole, even when the angular speed is disturbed at multiple time periods.

The SMC controller rise time, and overshoot for altitude, roll, pitch, and yaw are shown in Table 3.

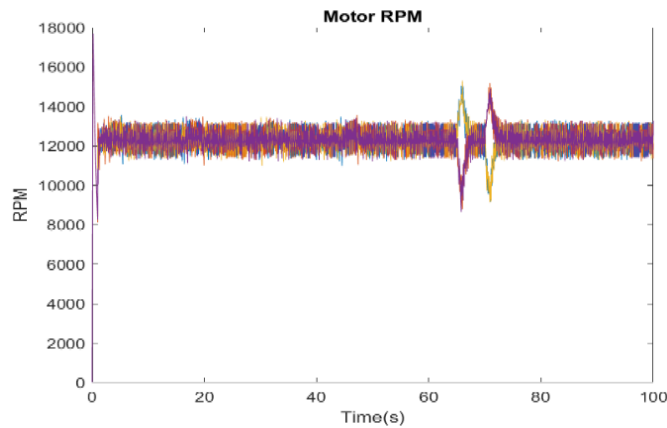


Fig. 11. Motors RPM

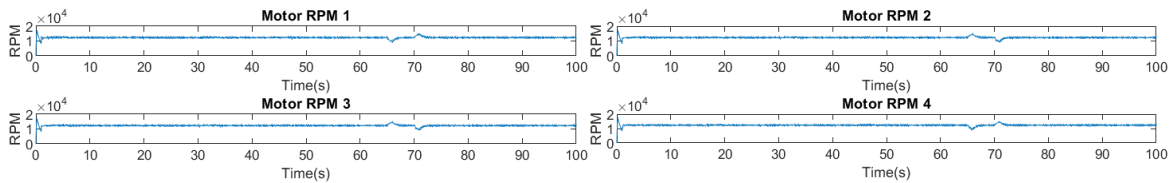


Fig. 12. Shows the speed of each motor (RPM)

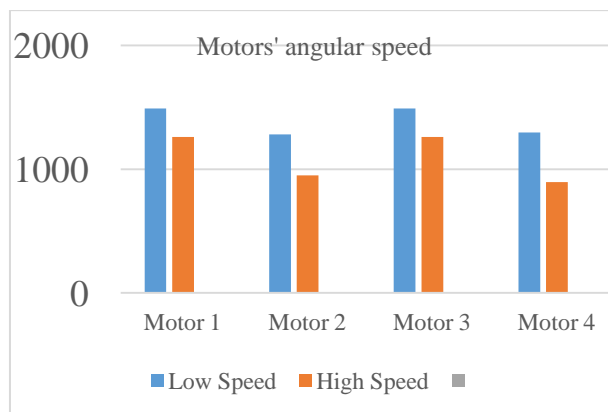


Fig. 13. Motors' angular speed comparison

Table 3. Controllers rise and overshoot

Measures	State	Rise time(ms)	Overshoot(%)
Altitude	-	-	-
Roll	-	202.724	120.852
Pitch	-	-	-
Yaw	-	792	0.505

6. CONCLUSION

In this study, a Sliding Mode Control (SMC) for quadcopter control is discussed in detail. The Newton-Euler equations are used to build a mathematical model for the control design. Fully and under-actuated subsystems may be found in the controller. There are two basic loops in the under-actuated subsystem (inner and outer), which are needed to control the x, y position so that correction blocks may give ϕ_d and θ_d , which are then delivered to control the vehicle's attitude. In the outer loop, a correction block is employed, whereas in the inner loop, SMC is used. Altitude and heading control are controlled by an SMC in the full-actuated subsystem. The controller's robustness is increased while also considering the impacts of quadcopter-induced external disturbances. The suggested controller alleviates the chattering phenomenon resulting by SMC. A comprehensive simulation study was undertaken, and the results are explained. As a result, the designed quadcopter can be controlled effectively using the suggested SMC controller.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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