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THEME

Fault Detection and Classification in Quadcopter Dynamics

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الملخص

لقد أحدثت الطائرات بدون طيار (UAVs) ثورة في التطبيقات عبر مختلف الصناعات، حيث أعادت تعريف الأساليب التقليدية لتنفيذ المهام. من بين نماذج الطائرات بدون طيار المتعددة، اكتسبت الطائرات الرباعية شعبية كبيرة بسبب تصميمها الفريد ذي الأربع مراوح، الذي يوفر استقراراً جوهرياً وقدرة على المناورة الاستثنائية. تساهم هذه الميزات في كفاءتها العالية في مجالات مختلفة من التطبيقات.

يركز هذا العمل على محاكاة نظام الطائرة الرباعية باستخدام وحدات تحكم PID والمنطق الضبابي في بيئة MATLAB/Simulink. يتم إجراء مقارنة شاملة للأداء، مع التركيز بشكل خاص على تقييم استجابات وحدات التحكم للأحداث غير المتوقعة أو الأعطال في نظام الطائرة الرباعية. تقدم النتائج رؤى قيمة حول متانة وموثوقية كل طريقة تحكم، مما يعزز من الإمكانيات لتحسين عمليات الطائرات بدون طيار.

الكلمات المفتاحية: الطائرات بدون طيار (UAVs) - الطائرات الرباعية - وحدات تحكم PID - المنطق الضبابي.

Abstract

Unmanned Aerial Vehicles (UAVs) have revolutionized applications across diverse industries, reshaping traditional approaches to task execution. Among the various UAV models, quadcopters have gained significant popularity due to their unique four-rotor design, which provides inherent stability and exceptional maneuverability. These features contribute to their high efficiency in a wide range of applications.

This work focuses on the simulation of a quadcopter system using PID and fuzzy logic controllers within the MATLAB/Simulink environment. A comprehensive performance comparison is conducted, particularly evaluating the controllers' responses to unexpected events or faults in the quadcopter system. The findings offer valuable insights into the robustness and reliability of each control method, enhancing the potential for optimized UAV operations.

Keywords: Unmanned Aerial Vehicles (UAVs) - Quadcopters - PID controllers - Fuzzy logic controllers.

Résumé

Les véhicules aériens sans pilote (UAVs) ont révolutionné les applications dans divers secteurs, en redéfinissant les approches traditionnelles de l'exécution des tâches. Parmi les différents modèles de UAVs, les quadricoptères ont gagné une popularité significative en raison de leur conception unique à quatre rotors, qui offre une stabilité inhérente et une maniabilité exceptionnelle. Ces caractéristiques contribuent à leur haute efficacité dans une large gamme des applications.

Ce travail se concentre sur la Matlab/Simulink d'un système de quadricoptère utilisant des contrôleurs PID et la logique floue dans l'environnement Simulink. Une comparaison complète des performances est effectuée, en évaluant particulièrement les réponses des contrôleurs aux événements inattendus ou aux pannes dans le système de quadricoptère. Les résultats offrent des informations précieuses sur la robustesse et la fiabilité de chaque méthode de contrôle, améliorant ainsi le potentiel d'optimisation des opérations des UAV.

Mots-clés : Véhicules aériens sans pilote (UAV) - Quadricoptères - Contrôleurs PID - Logique floue.

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Dedication

This dissertation is dedicated to my family for their unwavering encouragement and belief in my abilities, unconditional love. To myself, for the perseverance, dedication, and hard work that have brought this work to fruition.

To my friends, who provided much-needed encouragement and companionship. Your presence and positivity have been a source of comfort and joy during the challenging times.
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And finally, to all those who believe in the power of knowledge and the pursuit of excellence. Your passion and dedication inspire me to strive for greatness and continue learning. Thank you for being my inspiration and my support system.

BOUFATAH Sarah

Dedication

This dissertation is dedicated to my parents, whose unwavering support and encouragement have been my foundation throughout this journey. Your love and belief in me have been my greatest sources of strength and inspiration.

To my siblings, thank you for always standing by my side and believing in my dreams. And to myself, for the strength that carried me through every step, and the resilience that made this journey possible.

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MOHAMEDI Soumia Rim

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List of abbreviations

FLC Fuzzy Logic Controller

GCE Gain of the Center

GCU Gain of the Center for Unbounded Inputs

GE Gain of the Lower Bound

GPS Global Positioning System

GU Gain of the Upper Bound

PID Proportional, Integrative, and Derivative control

UAV Unmanned Aerial Vehicle

List of acronymes

ε : Absolute linear position of the quadcopter is defined in the inertial frame
θ : Pitch angle (the rotation of the quadcopter around the y-axis)
ϕ : Roll angle (the rotation of the quadcopter around the x-axis)
ψ : Yaw angle (the rotation of the quadcopter around the z-axis)
η : Angular position, is defined in the inertial frame
q : Linear and angular position vectors
V_B : Linear velocities in the body frame
v : Angular velocity in the body frame
R : Rotation matrix from the body frame to the inertial frame
W_n : Transformation matrix for angular velocities from the inertial frame to the body frame
G : Vector of the gravity
g : Gravity
T : Thrust motor on the quadcopter (in the body frame)
T_B : Total thrust on the quadcopter (in the body frame)
I_n : Inertia matrix (diagonal matrix)
τ : Motor torque
I : Input current
I_0 : No load current
k_t : Torque constant
P : Consumed power
V : Voltage drop across the motor
R_m : Motor resistance
ω : Motors angular velocity in the inertial frame
k_v : Constant of RMF generated per RPM
v_h : Air velocity
ρ : Density of the surrounding air
A : Swept area by the rotor
F_D : Frictional force
k_d : Frictional constant
A : Reference area (propeller cross-section, not area swept out by the propeller)
C_D : Dimensionless constant
R : Radius of the propeller
b : Appropriately dimensioned constant
τ_D : Torque due to drag
τ_z : Complete torque about the z axis for the i^{th} motor
τ_θ : Pitch torque
τ_ψ : Yaw torque
τ_ϕ : Roll torque
L_D : Distance from the center of the quadcopter to any of the propellers
I_M : Moment of inertia about the motor z axis
k : Appropriately dimensioned constant

General Introduction

Quadcopters are gaining popularity across various industries due to their flexibility and ease of use. They have become a preferred choice for many companies seeking efficient solutions. These devices, also known as Unmanned Aerial Vehicles (UAVs), can perform a wide range of tasks such as delivering packages, monitoring crops, conducting search and rescue missions and capturing aerial videos. The small size and agility of quadcopters make them indispensable in current operations. Their ability to navigate through challenging terrain and reach remote areas sets them apart. Companies worldwide are embracing quadcopter technology to enhance the effectiveness, speed, and accuracy of their operations[1].

A quadcopter is a machine that can fly without a pilot, but it needs a dependable control system to make this possible. In essence, a control system must control the rotors' velocity to let the vehicle fly stably and safely. This is because a quadcopter has a complicated dynamic model and is highly vulnerable to wind and other unforeseen environmental challenges [2].

In our dissertation , we will employ PID (Proportional-Integral-Derivative) and fuzzy logic controllers. Different principles employed to evaluate the quadcopters' stability as well as its fundamental roll, pitch, yaw, and altitude motions. We utilize these two control methodologies to explore their differences in managing the complexities of quadcopter dynamics.

To achieve the set objective, we will follow several essential steps:

- Firstly, we will provide an overview of quadcopters.
- Subsequently, we will see the controllers utilized in our study, PID (Proportional-Integral-Derivative) and fuzzy logic controllers, elucidating their fundamental principles.
- Following this, we will proceed to quadcopter modeling, outlining the mathematical representations.
- In the simulation phase, utilizing Simulink, we will simulate the quadcopter system with PID controllers, endeavoring to determine the optimal PID gains. Similarly, we will conduct simulations with fuzzy logic controllers, aiming to identify suitable scaling factors. Then we will compare the performance of these two controllers. We will also analyze how

these two controllers react to unexpected events or faults occurring in the quadcopter system.

At the end of this work, a general conclusion will be provided along with some suggestions for future study and development.

Chapter 1

Modeling, Control, and Fault Analysis in Quadcopter Dynamics

1.1 Introduction

A quadcopter is a type of unmanned aerial vehicle (UAV) or drone that is lifted and propelled by four rotors. Quadcopters are highly maneuverable and versatile, capable of hovering, flying in any direction, and performing a variety of tasks such as aerial photography, surveillance, and package delivery. They are commonly used in both recreational and commercial applications due to their stability, agility, and ease of control. In this chapter, we begin by providing an overview of quadcopters. We then introduce the PID and fuzzy logic controllers, explaining their fundamental principles. Next, we discuss quadcopter modeling, followed by simulation using Simulink. Through simulations with PID and fuzzy logic controllers, we aim to determine optimal gains and scaling factors respectively. Finally, we compare the performance of these controllers and analyze their response to unexpected events in the quadcopter system.

1.2 Quadcopter

A quadcopter, also known as a quadrotor, is an unmanned aerial vehicle (UAV) distinguished by its four rotors arranged in either a square or X-shaped configuration. Each rotor is attached to a motor and a propeller, which allows the quadcopter to lift off the ground and maneuver in the air. Quadcopters can be controlled remotely or programmed to fly autonomously. The quadcopter shown in Figure 1.1.

The basic components[3] of a quadcopter are given bellow :

- The frame provides the structure and support for mounting the motors, propellers, and other components.

- Motors and propellers: generate thrust and lift, enabling the quadcopter to take off and fly.

- Flight controllers: often equipped with advanced algorithms, maintain stability and precise control during flight by adjusting the rotor speed based on sensor feedback.

- Battery: batteries in quadcopters, usually lithium-based, are crucial for powering flight and onboard systems due to their energy density and weight advantages. They significantly influence flight duration, payload capacity, and maneuverability, requiring efficient management for optimal performance.

- ESC:Electronic Speed Controllers (ESCs) control motor speed in quadcopters by translating signals from the flight controller into specific RPMs. They are essential for stable flight dynamics, ensuring precise maneuverability and responsiveness. ESCs are integral to optimizing the overall performance and efficiency of quadcopters.

In addition to various sensors such as gyroscopes, accelerometers, and GPS.

The quadcopters are governed by the laws of physics and aerodynamics. These unmanned aerial vehicles rely on the variation of rotor speeds to produce the basic movements required for their operation, namely roll, pitch, yaw, and altitude control[1], which provide ample control to manage all six degrees of freedom of the quadcopter.

Quadcopters have found widespread applications across various industries and sectors due to their stable flight performance, including aerial photography and videography, surveillance and security, search and rescue, agriculture, recreation, and hobbies.

Figure 1.1: A Modern Quadcopter [4]

1.3 Mathematical modelling

Controlling a quadcopter is a challenging task. Despite having six degrees of freedom (three for translation and three for rotation), quadcopters only have four independent inputs, which makes them underactuated. Achieving motion in all six directions involves a coupling of rotational and translational movements, leading to highly nonlinear dynamics, especially when considering complex aerodynamic effects [2]. Unlike ground vehicles, quadcopters lack significant friction to naturally slow down, so they must generate their own damping to stop and stay stable.

1.3.1 Frames

The quadcopter's exact location in space is determined by its linear and angular position. Its linear position within the inertial frame's x, y and z axes. Its angular position, on the other hand,is defined in the inertial frame with three Euler angles (η):pitch θ, roll ϕ and yaw ψ,with q a vector contains the linear and angular position victors.

$$\varepsilon = \begin{bmatrix} x \\ y \\ z \end{bmatrix}, \eta = \begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix}, q = \begin{bmatrix} \varepsilon \\ \eta \end{bmatrix} \tag{1.1}$$

1.3.1.1 Yaw angle

Describes a rotational action in which the quadcopter spins to the left or right on its vertical axis, controlled by adjusting the speed of one side of the drone's rotors while simultaneously slowing down the other.

1.3.1.2 Pitch angle

Describes a forward or backward movement where the quadcopter tilts forward or backward and moves accordingly. This motion is controlled by altering the speed of the front or rear rotors.

1.3.1.3 Roll angle

A roll refers to a lateral movement where the quadcopter tilts to one side and moves in that direction. This is achieved by adjusting the speed of the rotors on one side of the drone, causing it to tilt.

1.3.2 Kinematics

The kinematics of a quadcopter lay the groundwork for understanding its motion in both the body and inertial frames. This section explores the linear and angular velocities and the relationship between the two frames.

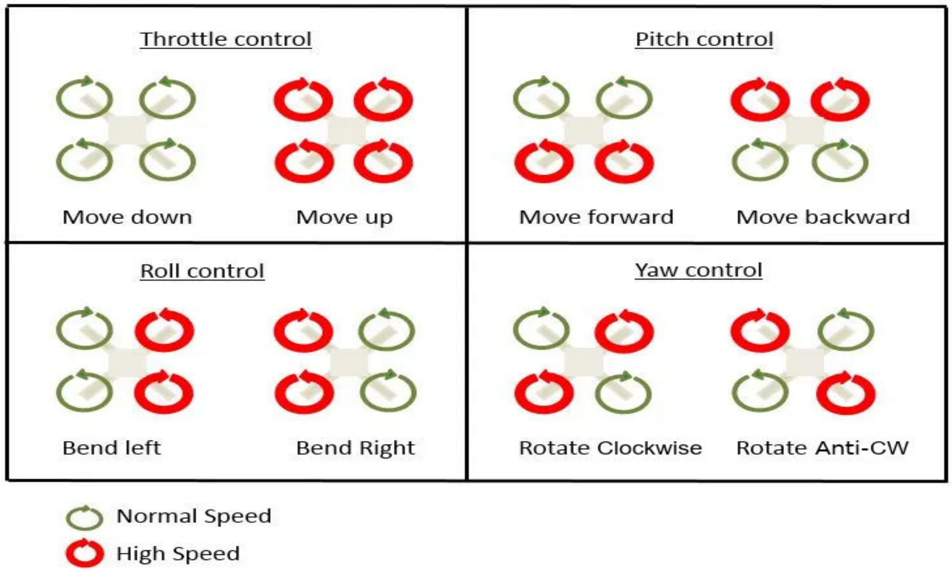

Figure 1.2: Quadcopter movements and control [5]

The linear velocities V_B, given by :

$$V_B = \begin{bmatrix} V_x, B \\ V_y, B \\ V_z, B \end{bmatrix} \tag{1.2}$$

The angular velocities v, given by :

$$v = (p, q, r)^T \tag{1.3}$$

The rotation matrix from the body frame to the inertial frame is given by :

$$R = \begin{bmatrix} C_\psi C_\theta & C_\psi S_\theta S_\phi - S_\psi C_\phi & C_\psi S_\theta C_\phi - S_\psi S_\phi \\ S_\psi C_\theta & S_\psi S_\theta S_\phi + C_\psi C_\phi & S_\psi S_\theta C_\phi + C_\psi S \\ -S_\theta & C_\theta S_\phi & C_\theta C_\phi \end{bmatrix} \tag{1.4}$$

The transformation matrix for angular velocities from the inertial frame to the body frame is W_η , given by :

$$W_n = \begin{bmatrix} 1 & 0 & -S_\phi \\ 0 & C_\phi & C_\phi S_\theta \\ 0 & -S_\phi & C_\theta C_\phi \end{bmatrix} \tag{1.5}$$

1.3.3 Acceleration

The dynamics of a rigid body, such as a quadcopter, can be described using the Newton-Euler formalization to calculate its acceleration.

In the body frame, the force needed for mass acceleration and the centrifugal force equal gravity, and the total rotor thrust.

$$m\dot{V}_B + v \times (mV_B) = R^{\mathrm{T}} G + T_B \tag{1.6}$$

However, in the inertial frame, the centrifugal force is nullified, leaving only gravity and the thrust magnitude and direction contributing to the quadcopter's acceleration.

$$m\ddot{\varepsilon} = G + RT_B \tag{1.7}$$

After analyzing and simplifying equations based on the Newton-Euler principles and relationships, the angular acceleration of the quadcopter is defined as follows:

$$\ddot{\eta} = \begin{bmatrix} 0 & \dot{\phi}C_\phi T_\theta + \dot{\theta}S_\phi/C_\theta^2 & -\dot{\phi}S_\phi C_\theta + \theta C_\phi/C_\theta^2 \\ 0 & -\dot{\phi}S_\phi & -\dot{\phi}C_\phi \\ 0 & \dot{\phi}C_\phi/C_\theta + \dot{\phi}S_\phi T_\theta/C_\theta & -\dot{\phi}S_\phi/C_\theta + \dot{\theta}C_\phi T_\theta/C_\theta \end{bmatrix} v + W_\eta^{-1}\dot{v} \tag{1.8}$$

1.3.4 Physics

It is necessary to know the physical features in order to represent the dynamics of the system. We'll start by describing the quadcopter's motors. All quadcopter motors are identical, allowing us to analyze one without loss of generality. adjacent propellers spin in opposite directions to balance torques. For instance, if one propeller rotates clockwise, its adjacent ones rotate counterclockwise.

1.3.4.1 Motors

The brushless motor in quadcopter is to provide the necessary propulsion by converting electrical energy into mechanical motion. By spinning the propellers, it generates the thrust required for flight. The simplified equation of motor's power (the motor's resistance is negligible) can be find as:

$$P \approx \frac{(\tau + k_t I_0)\, k_v \omega}{k_t} \tag{1.9}$$

1.3.4.2 Forces and Torques

We must represent the forces and torques applied to the quadcopter and motor frame.

For all the motors we have the total thrust is given by:

$$T_B = \sum_{i=1}^{4} T_i = k \begin{bmatrix} 0 \\ 0 \\ \sum \omega_i^2 \end{bmatrix} \tag{1.10}$$

The global drag forces defined by:

$$F_D = \begin{bmatrix} -k_{d,x}\dot{x} \\ -k_{d,y}\dot{y} \\ -k_{d,z}\dot{z} \end{bmatrix} \tag{1.11}$$

the torques in the body frame are:

$$\tau_B = \begin{bmatrix} L_D k\left(\omega_1^2 - \omega_3^2\right) \\ L_D k\left(\omega_2^2 - \omega_4^2\right) \\ b\left(\omega_1^2 - \omega_2^2 + \omega_3^2 - \omega_4^2\right) \end{bmatrix} \tag{1.12}$$

for the quadcopter we have:

$$\tau = \tau_B = J\ddot{\eta} + \frac{d}{dt}(J)\dot{\eta} - \frac{1}{2}\frac{\partial}{\partial \eta}\left(\dot{\eta}^T J \dot{\eta}\right) = J\ddot{\eta} + C(\eta, \dot{\eta})\dot{\eta} \tag{1.13}$$

1.3.4.3 Aerodynamic effects

To enhance the realism of the quadcopter's behavior, drag force caused by air resistance is incorporated:

$$\begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = -g \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} + \frac{T}{m} \begin{bmatrix} C_\psi S_\theta C_\phi + S_\psi S_\theta \\ S_\psi S_\theta C_\phi - C_\psi S_\phi \\ C_\theta C_\phi \end{bmatrix} - \frac{1}{m} \begin{bmatrix} A_x & 0 & 0 \\ 0 & A_y & 0 \\ 0 & 0 & A_z \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} \tag{1.14}$$

1.4 PID controller

In industrial environments, PID controllers are commonly used to provide precise process control under various process conditions, they use control loop feedback in industrial and control systems applications[6]. The controller initially calculates the error between a measured process variable and a desired set point. It then attempts to minimize this error by adjusting the control inputs or outputs within the process, thereby bringing the process variable closer to the desired value [7]. This approach works well when the process or control's mathematical model is complex for the system, in order improve performance, for example, by making the system more responsive, PID parameters need to be modified based on the particular application.

Designing a PID system involves choosing the structure of the PID controller and choosing numerical values for the PID parameters. These three constants are the derivative, integral, and proportional ones for the PID algorithm. The proportional constant (P) responds to the current error, the integral constant (I) responds to the sum of recent errors, and the derivative constant (D) responds to the rate of change of errors. These three actions are then used to adjust the process [7].

Essentially, PIDs controllers are an equation that the controller uses to evaluate the controlled variables:

$$u(t) = P(t) + I(t) + D(t) \tag{1.15}$$

$$P(t) = K_p \cdot e(t) \tag{1.16}$$

$$I(t) = K_i \int_0^t e(\tau) d\tau \tag{1.17}$$

$$D(t) = K_d \frac{de(t)}{dt} \tag{1.18}$$

1.5 Fuzzy logic controller

Fuzzy logic provides a computational framework for handling uncertainty and imprecision in the process of decision-making. In contrast to conventional binary logic, which relies on exact true or false values, fuzzy logic enables the expression of imprecise or unclear ideas. It includes using fuzzy sets to reason[8]. The theory of fuzzy sets is based on the notion of partial membership: each element belongs partially or gradually to the fuzzy sets that have been defined [9],the degree of membership or relevance of a value to a fuzzy set describe by membership functions.

A fuzzy logic controller (FLC) is a type of control system that employs fuzzy logic to make decisions and control processes. FLCs consist of three main components: fuzzification, rule evaluation and defuzzification.

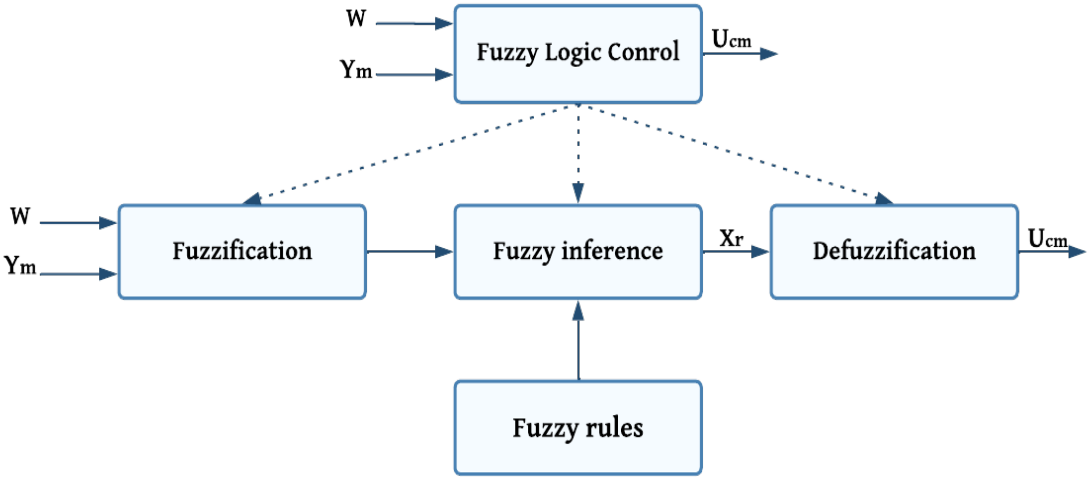

Figure 1.3: fuzzy logic control

1.5.1 Fuzzification

Fuzzification is the process of transforming precise input data into fuzzy sets, which represent linguistic variables. These fuzzy sets allow for the representation of uncertain or imprecise information, facilitating reasoning in fuzzy logic systems.

1.5.2 Fuzzy inference and rule base

In fuzzy logic systems, fuzzy inference and the rule base play crucial roles in decision-making. Fuzzy inference utilizes rules from the rule base, established by experts, to interpret input data and determine appropriate actions. These rules define how input variables influence output variables, guiding the system's decision-making process. For example, consider a temperature control system with rules like "if it's cold and humid, increase the heater output." When the system detects low temperature and high humidity, fuzzy inference applies these rules to decide the best course of action, such as adjusting the heater to increase the heater output.

1.5.3 Defuzzification

Conversion, after inference, of a fuzzy set of a linguistic output variable into a numerical value [9], actionable decisions or control actions. This process determines the most appropriate crisp output value from the fuzzy output set, enabling practical implementation of the system's decisions. Various defuzzification methods, such as centroid, weighted average, or maximum membership, are employed to achieve this conversion effectively.

Fuzzy logic controllers have been successfully applied in various fields, including industrial automation, robotics, automotive systems, and consumer electronics, due to their ability to handle complex, nonlinear systems and adapt to changing environments.

To control the quadcopter's movements and behavior in simulation environments, we need to adjust the scaling factors (GE : Gain of the Lower Bound, GCE :Gain of the Center, GU :Gain of the Upper Bound, and GCU :Gain of the Center for Unbounded Inputs), which play crucial roles in normalizing input variables for the fuzzy controller.

1.6 Quadcopter Fault Types

1.6.1 Motor Failure

Motor failure in quadcopters poses significant risks to flight safety and stability, potentially leading to loss of control and crashes. Various factors such as overheating, wear, manufacturing defects, or external damage can contribute to motor failures. Detecting these failures promptly is critical for preventing accidents. Advanced fault detection and diagnosis systems analyze data from onboard sensors to identify motor failures in real-time and trigger appropriate responses, such as adjusting thrust or initiating emergency landing procedures. Implementing tailored fault detection and diagnosis systems is crucial for mitigating risks associated with motor failures in quadcopters [10].

1.6.2 Sensor Errors

Quadcopters depend on various sensors like accelerometers, gyroscopes, and barometers for stability and navigation. Errors in these sensors can occur due to temperature changes, magnetic interference, or manufacturing flaws. These errors can lead to inaccurate readings, causing the flight control system to make wrong adjustments. To reduce the impact of sensor errors, modern quadcopters use advanced algorithms that merge data from multiple sensors, offering more precise and dependable information [11].

1.6.3 Disturbances

Quadcopters face disturbances in their surroundings, such as wind gusts, turbulence, or even their own propeller wash. To counter these disruptions, advanced flight control systems use complex algorithms to continuously analyze the quadcopter's position and speed. These algorithms make instant adjustments to the quadcopter's thrust and rotor speeds to maintain stability and control. Some quadcopters are equipped with GPS systems, allowing them to hover accurately at a specific spot, even in challenging conditions.

1.6.4 Battery Issues

When using electric drones, one of the most concerned issues is about the battery last and the endurance of the drone [12].These issues can arise from excessive use, low-quality batteries, or extreme temperature changes. When a quadcopter's battery malfunctions, it may unexpectedly lose power during flight, leading to a potential crash.

1.6.5 Propeller Damage

Damage to propellers is a common issue encountered by quadcopter owners. It can occur due to collisions with objects, improper landings, or normal wear and tear. Damaged propellers can disrupt the quadcopter's lift and control, making it challenging to maintain stability while flying.

In this work, we aim to enhance the performance of quadcopters by focusing on three significant challenges: motor failure, sensor errors, and disturbances. Through our focus on these three challenges, we contribute to the advancement of quadcopter technology and pave the way for its widespread adoption in diverse applications.

1.7 Simulation results and discussions

Our objective is to control the stability of the quadcopter system using different controllers such as PID and fuzzy PID. To this end , a simuluation was conducted using Matlab/Simulink environment.

The global control Schema block combines several essential elements for controlling the quadcopter's actions. It includes an "inputs" block, providing the reference signals. The "Quadcopter 3D Model" block simulates the quadcopter's dynamics. A "Controller" block and "Error Calculation" block computes the disparity between reference values and actual measurements. The overall block is shown in Figure.1.4.

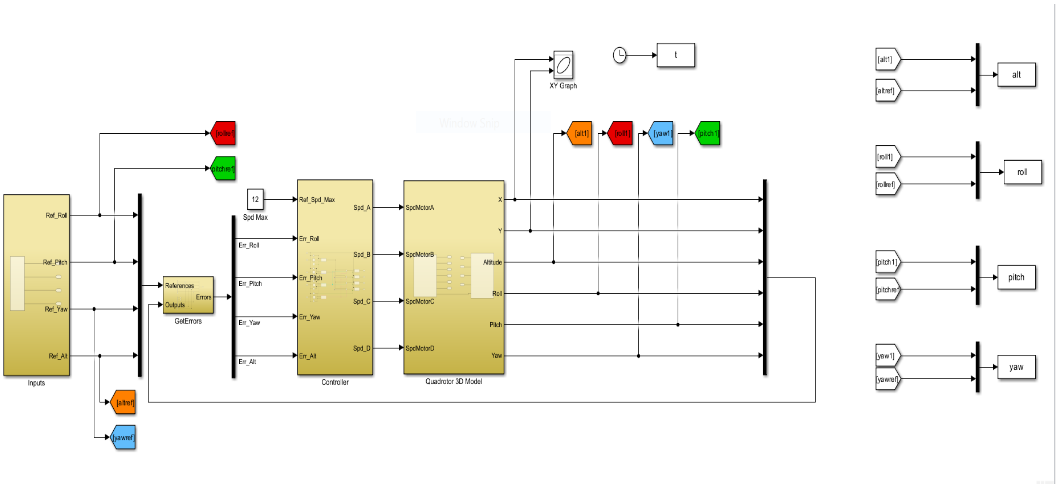

Figure 1.4: Global Schema Block of the quadcopter

In this simulation, the reference block plays an important role in providing input signals that specify the desired orientation angles (roll, pitch, yaw) and altitude for the aircraft. These signals are essential for controlling the quadcopter's behaviors and making sure it precisely maintains the required flight parameters. Referance Block shown in Figure 1.5 and the possible scenario of altitude, pitch, roll, and yaw is shown in figure 1.6.

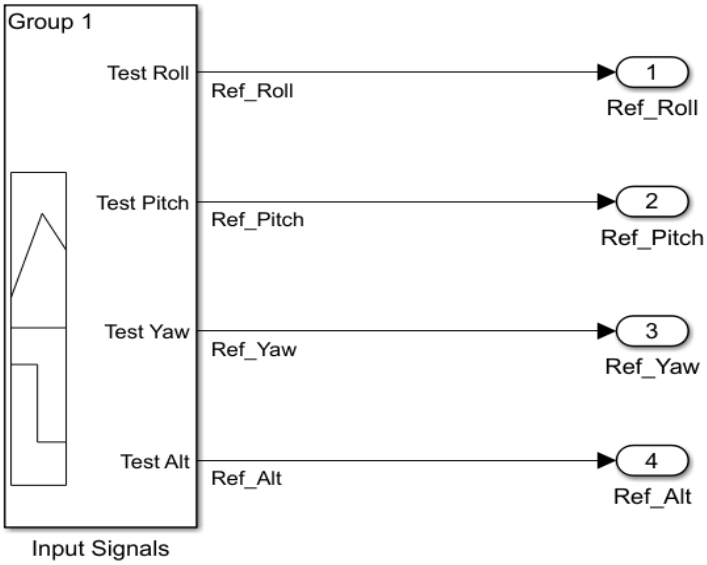

Figure 1.5: Input Block

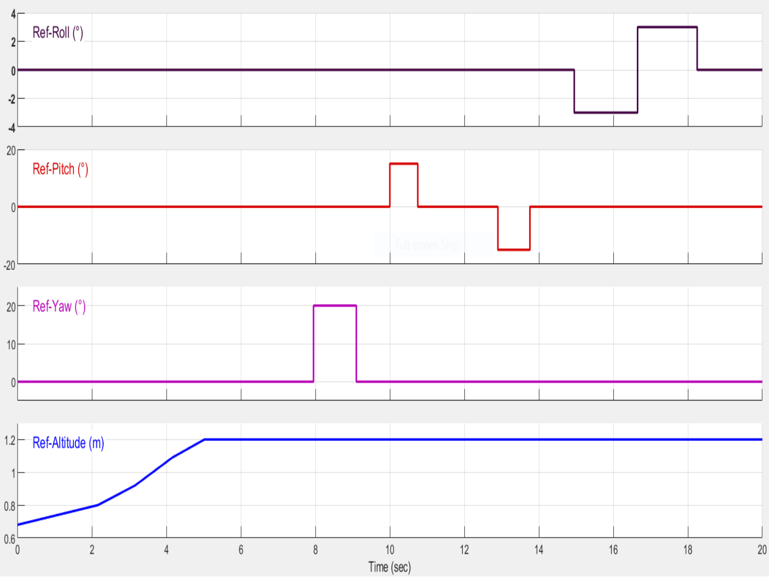

Figure 1.6: Trajectory of altitude, pitch, roll, and yaw

The "Quadcopter Model" block in the simulation represents the physical dynamics and characteristics of the quadcopter.

Quadcopter Model Block shown in Figure 1.7.

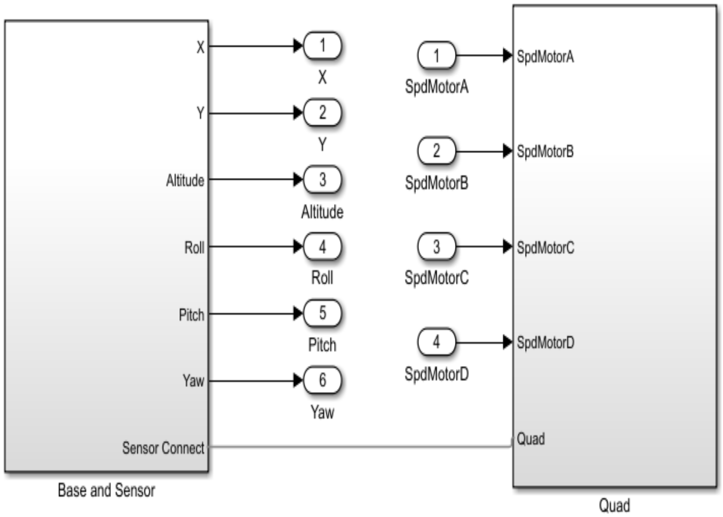

Figure 1.7: Quadcopter 3D Model Block

1.7.1 Simulation with PID

Within the PID controller block, individual "cmd" blocks correspond to specific angles (roll, pitch, yaw) alongside altitude commands. Additionally, there are parameter-setting blocks to configure PID values for each angle (We achieve optimal gains settings manually by adjusting them until achieving optimal performance).

PID controller Block shown in Figure.1.8.

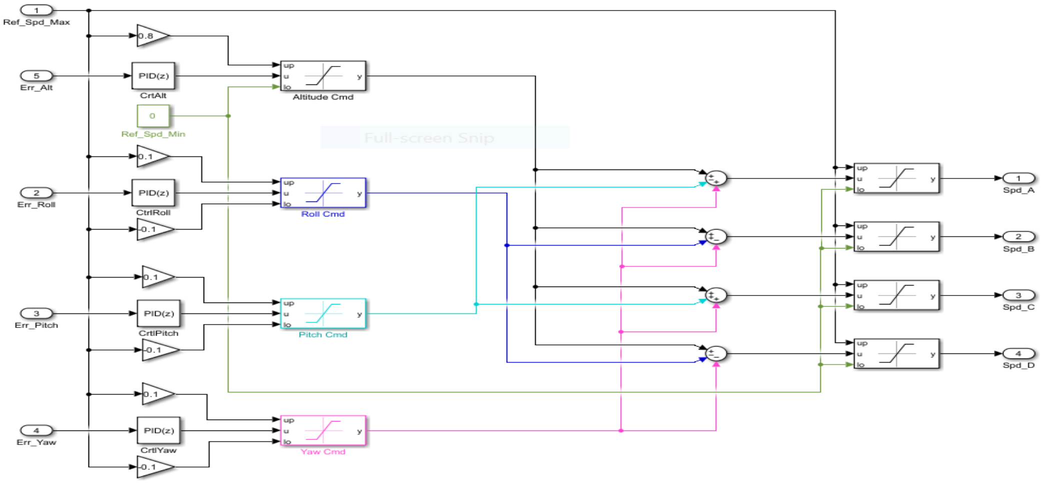

Figure 1.8: PID Controller Block

1.7.2 Simulation with fuzzy logic

The “Fuzzy PID” block incorporates a fuzzy interface system to adjust scaling factors between proportional-integral (PI) and proportional-derivative (PD) control components. This fuzzy PID control block is shown in in Figure 1.9.

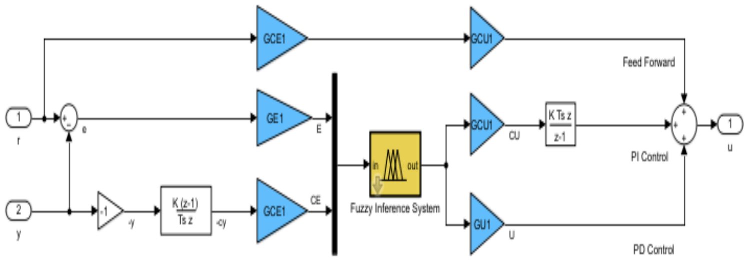

Figure 1.9: Fuzzy PID Block

Additionaly , we applied this to the overall control block, replacing the classic PID with the fuzzy one as shown in Figure 1.10.

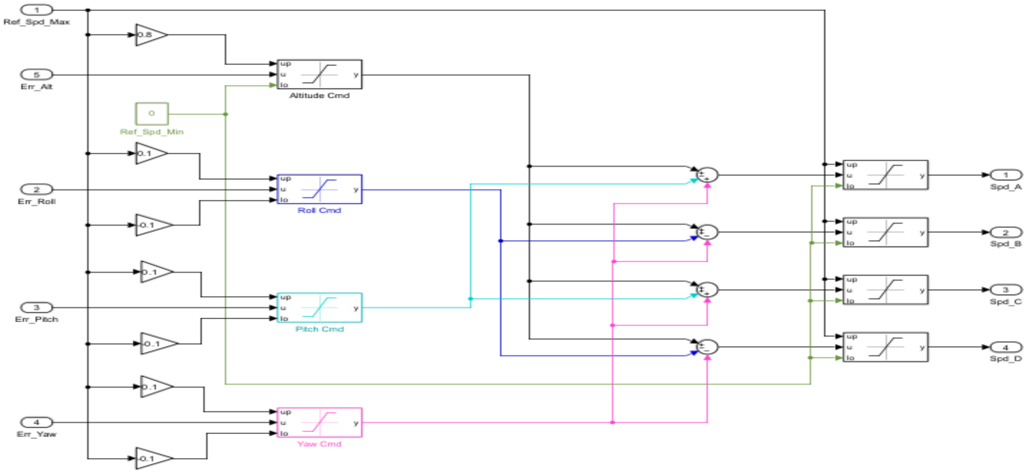

Figure 1.10: Controller Block

1.7.3 Testing and results

In our simulation we have tried varying scaling factor values, including optimal, lower, and higher inputs for the controller parameters , for each of the following angles: pitch, roll, yaw, and altitude. Scaling factor values are presented in the subsequent tables.
The following are the parameters for the Fuzzy logic controller:

We conducted simulations with varying PID gains values, including optimal, lower, and higher, for each of the following angles: pitch, roll, yaw, and altitude. PID gains values are presented in the subsequent tables.
The following are the parameters for the Fuzzy logic controller:

Table 1.1: Pitch PID parameters

	<<	Opt	<<
Kp	0.01	2	10
Ki	0.001	0.06	6
Kd	0.001	0.05	5

Table 1.2: Roll PID parameters

	<<	Opt	<<
Kp	0.1	1	10
Ki	0.005	0.03	1
Kd	0.0003	0.02	0.3

Table 1.3: Yaw PID parameters

	<<	Opt	<<
Kp	0.1	8	14
Ki	0.0001	0.01	1
Kd	0.0005	0.05	5

Table 1.4: Altitude PID parameters

	<<	Opt	<<
Kp	20	60	61
Ki	0.001	0.3	70
Kd	1	12	90

1.7.4 Visualization of Quadcopter Simulation Results

When employing the PID controller with optimal values, the system output closely follows the reference signal, albeit with some oscillations. This observation solidifies the effectiveness of the

PID controller in ensuring reference tracking.Optimal PID result shown in Figure.1.11

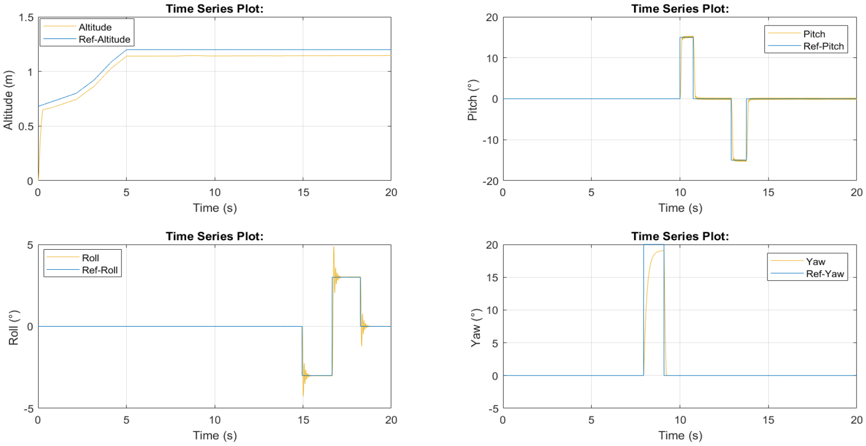

Figure 1.11: PID optimal result

In our simulation study, we investigated what happens when we use lower than optimal values for the PID controller. We found that although the roll, yaw, pitch, and altitude mostly followed the target signal, there were some oscillations and a significant static error in altitude, along with a few oscillations in roll.

From this, when operated with values below the optimal range, still maintains a certain level of reference tracking capability. Lower PID results shown in Figure1.12.

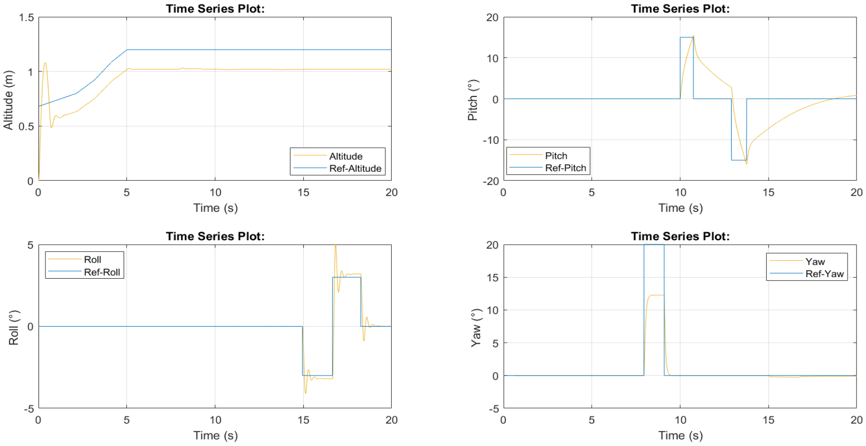

Figure 1.12: PID lower result

In our simulation study, we examined how using values above the optimal value for the PID controller affected the system. The findings showed that although the roll, yaw, pitch, and altitude roughly tracked the reference signal, there were noticeable oscillations in the pitch and yaw angles.

This suggests that even when the PID controller operates with values exceeding the optimal range, it retains some ability to track the reference. However, the significant oscillations imply that the system's response lacks stability or precision. Higher PID results shown in Figure 1.13.

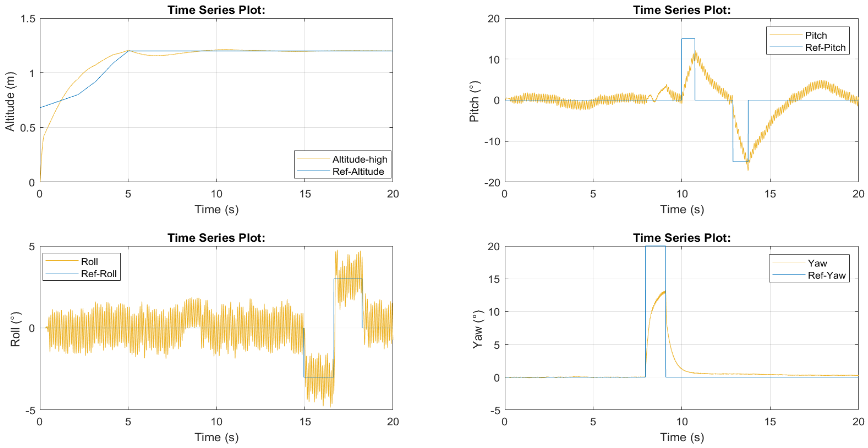

Figure 1.13: PID higher result

When employing the fuzzy controller(optimal values), the system output closely follows the reference signal, albeit with slight response delay. This confirms the effectiveness of the fuzzy controller in achieving reference tracking. Optimal fuzzy result shown in Figure 1.14.

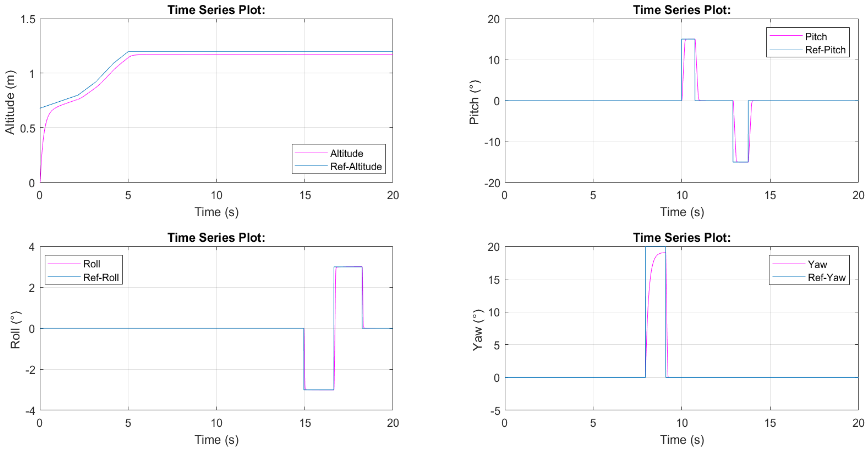

Figure 1.14: Fuzzy optimal result

In our simulation analysis, we explored the effects of using lower than optimal values for the fuzzy controller. The results revealed that while the roll, yaw, pitch, and altitude approximately followed the reference signal, there were notable oscillations present in the system's behavior, additionally, it was observed that the altitude static error is greater when operated with lower values.

This observation suggests that the fuzzy controller, when operated with values below the optimal range, still maintains a certain level of reference tracking capability. However, the presence of significant oscillations indicates that the system's response is not as stable or precise. Lower fuzzy results shown in Figure 1.15.

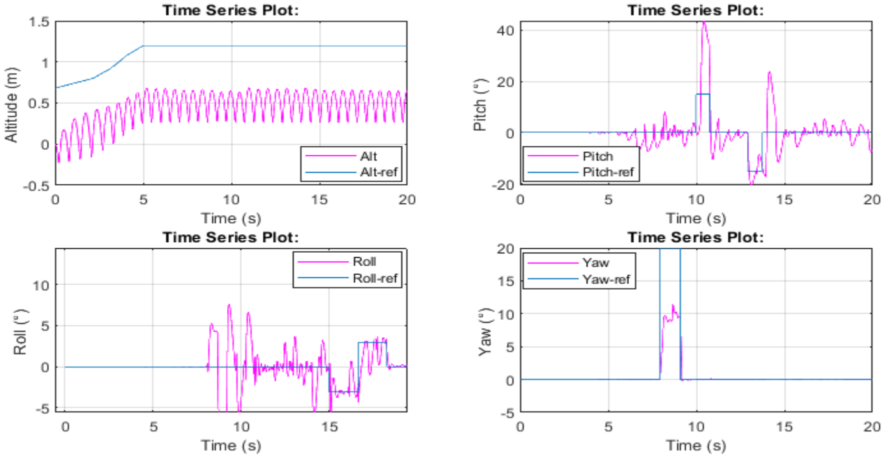

Figure 1.15: Fuzzy lower result

We performed simulations with scaling factors higher than optimal. The results of this simulation indicate that although roll, yaw, pitch, and altitude effectively follow the reference signals, there is a notable rise in response time when the controller values exceed the optimal values. Higher fuzzy results shown in Figure 1.16.

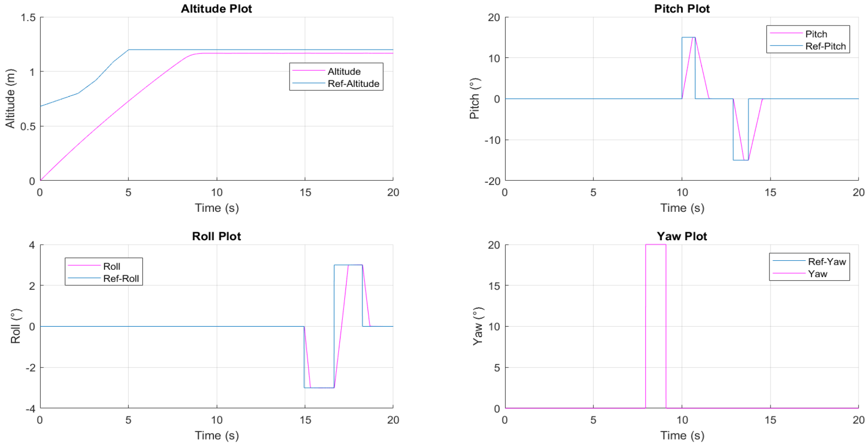

Figure 1.16: Fuzzy higher result

In our study, we conducted simulations using both PID and fuzzy controllers and compared the results of each simulation. The comparison results, as depicted in Figure.1.17, show that both controllers were effective in ensuring that the system's output closely tracked the desired reference signal.

We observed that the PID controller's results exhibited reference tracking with oscillations. Conversely, the fuzzy controller effectively tracked the system without oscillations, though with an increased response time, as shown in Figure.1.17.

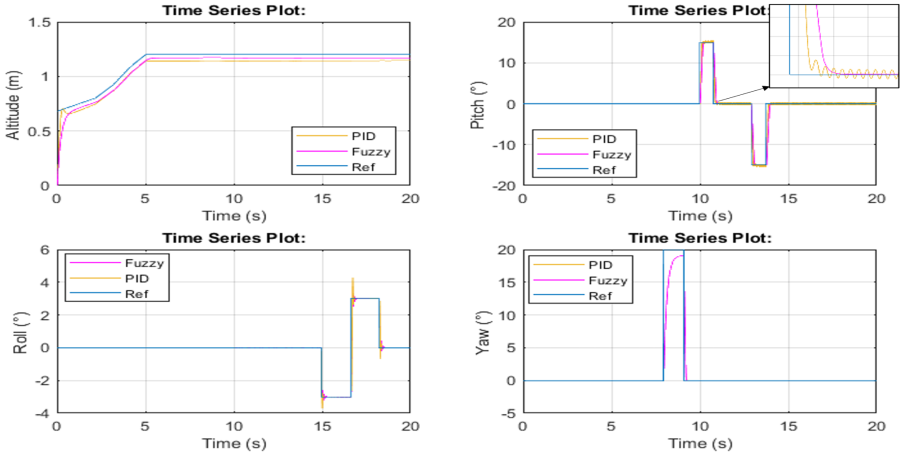

Figure 1.17: Comparison of Optimal PID and Fuzzy Logic Responses against the reference

1.7.5 Simulation Results of Quadcopter Faults

1.7.5.1 Motor Failure

To simulate motor faults in the Matlab, we connected motors with gains of 0.8 then 0.2.

- Motor Faults with 0.8 gain

Introducing a fault in the first motor of the quadcopter with a 0.8 gain results in observable effects on the pitch and yaw dynamics.The pitch graph displays minor oscillations, the yaw graph indicates a significant decrease from the optimal value, results shown in Figure 1.18.

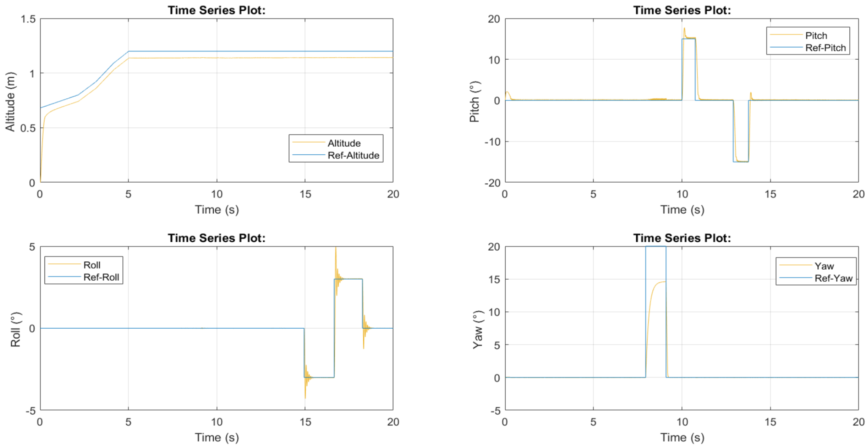

Figure 1.18: First motor failure with 0.8 gain

In the second motor the result displays a little oscillation in pitch, The roll initially deviates significantly from the reference, then returns but remains close to the reference value without precisely reaching it along with oscillations, while yaw returns towards the reference value. results shown in Figure 1.19.

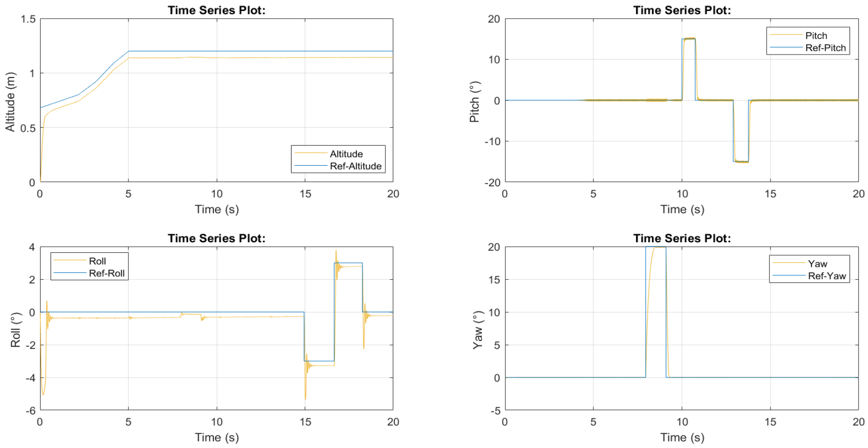

Figure 1.19: Second motor failure with 0.8 gain

The output of the third motor fault is the same as that of the first. results shown in Figure 1.20.

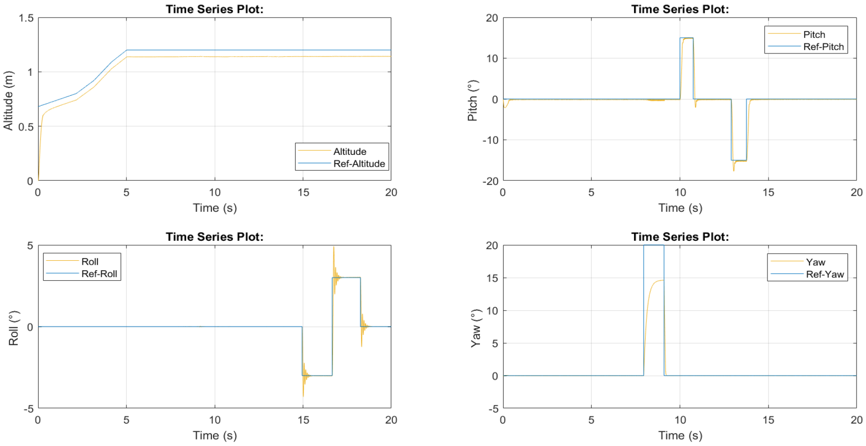

Figure 1.20: Third motor failure 0.8 gain

The results of the fourth motor is the same as that of the second one. results shown in Figure 1.21.

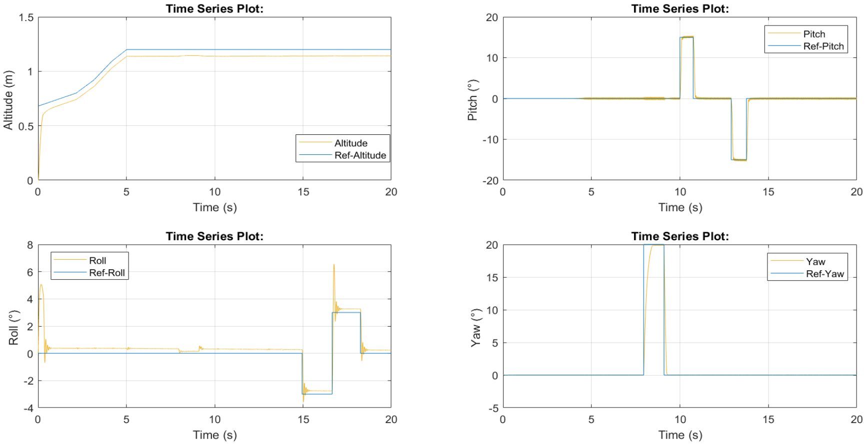

Figure 1.21: Fourth motor failure with 0.8 gain

- Motor Faults with 0.2 gain

Introducing a fault in the quadcopter's first motor with a gain of 0.2 leads to significant effects on pitch, yaw, roll, and altitude dynamics. The graph illustrates that yaw, pitch, and altitude do not follow the reference signal, exhibiting large oscillations. However, it is noted that roll is still capable of tracking the reference signal, albeit with significant oscillations.results shown in Figure 1.22.

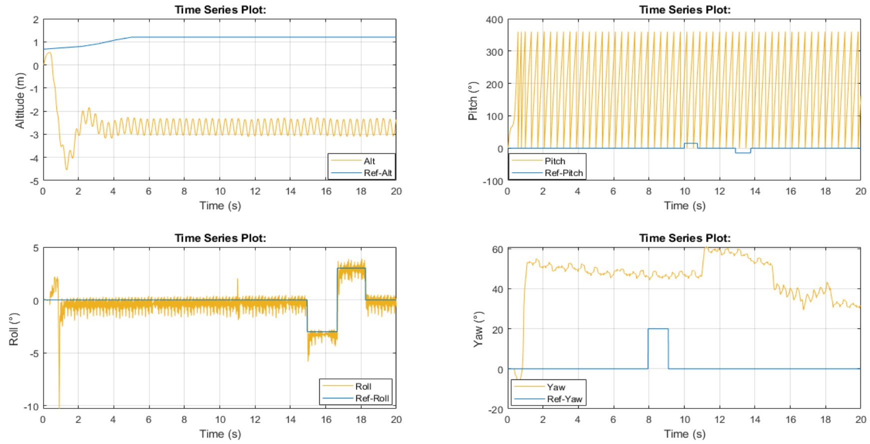

Figure 1.22: First motor failure with 0.2 gain

Introducing a fault in one of the remaining three motors of the quadcopter with a gain of 0.2, as depicted in Figure.1.23, 1.24, and 1.25, results in roll, pitch, yaw, and altitude not following the reference signal, accompanied by significant oscillations in each of them.

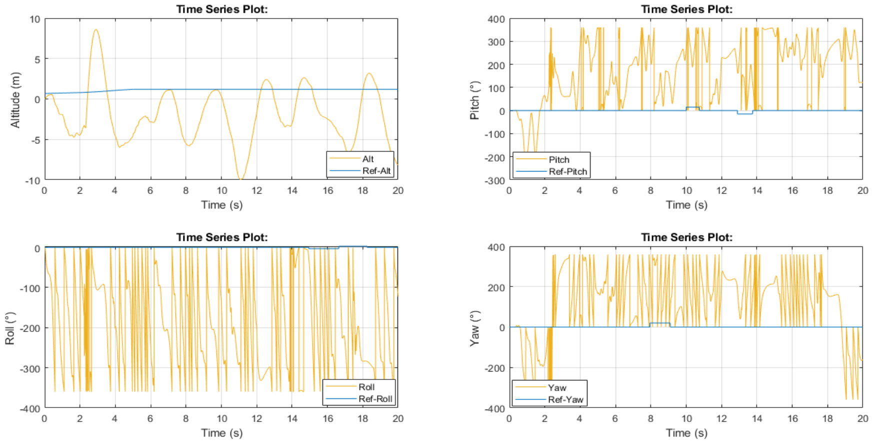

Figure 1.23: Second motor failure with 0.2 gain

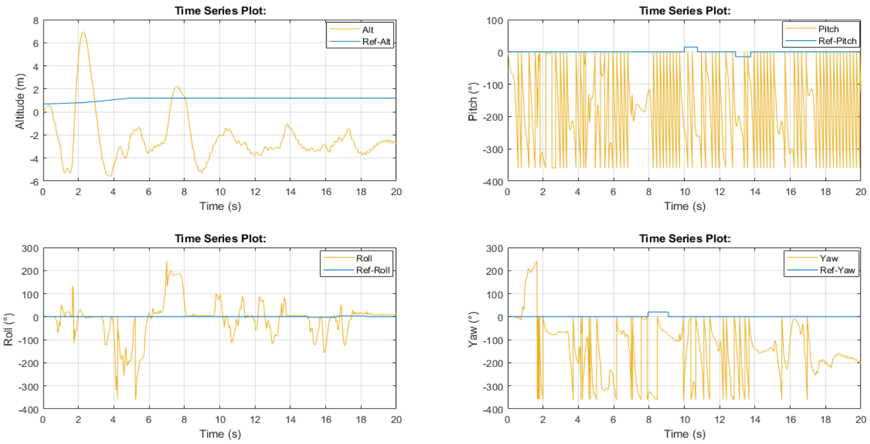

Figure 1.24: Third motor failure with 0.2 gain

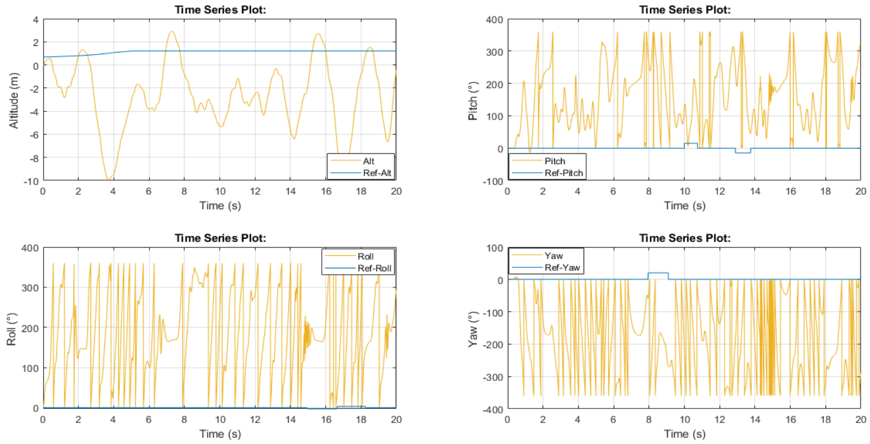

Figure 1.25: Fourth motor failure with 0.2 gain

1.7.5.2 Sensor Errors

In the context of sensor-type faults simulate within MATLAB, White noise blocks incorporated into the altitude, yaw, roll and pitch inputs then outputs to simulate sensor faults.

- Input sensor errors

For altitude sensor input fault: We observe that the reference signal of altitude display a white noise pattern, with the output trajectory closely following this reference and cause oscillations in yaw, pitch, and roll outputs. results shown in Figure 1.26.

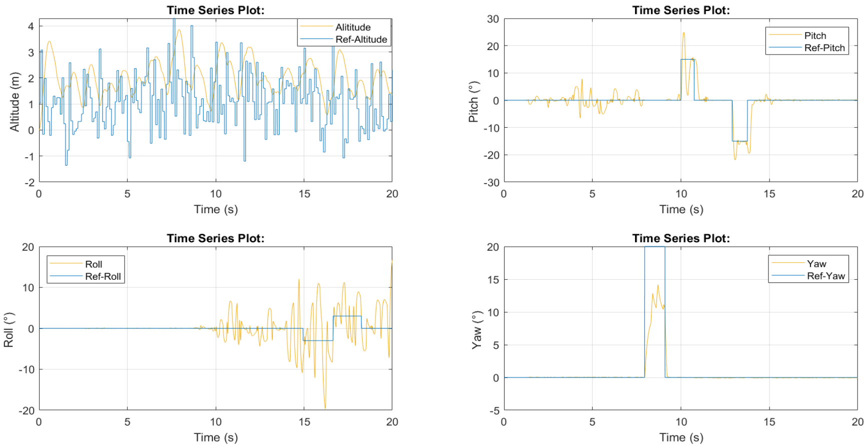

Figure 1.26: Altitude input sensor errors

For pitch sensor input fault: We observe that the reference signal of pitch display a white noise pattern, with the output trajectory closely following this reference and cause some oscillations in roll output. results shown in Figure 1.27.

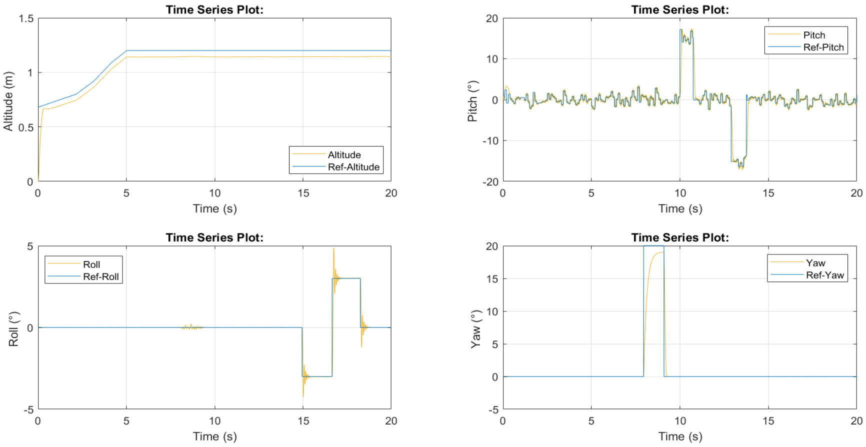

Figure 1.27: Pitch input sensor errors

For roll sensor input fault: We observe that the reference signal of roll display a white noise pattern, with the output trajectory closely following this reference and cause some oscillations in pitch output. results shown in Figure.1.28

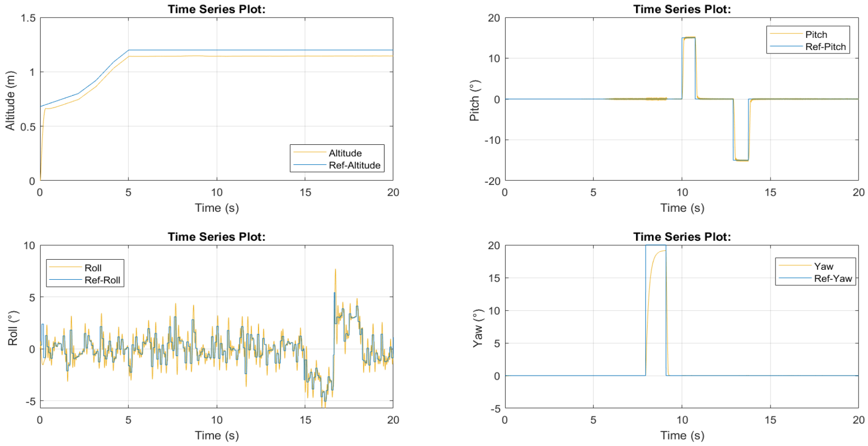

Figure 1.28: Roll input sensor errors

For yaw sensor input fault: We observe that the reference signal of yaw display a white noise pattern, with the output trajectory closely following this reference and cause some oscillations in roll and pitch outputs. results shown in Figure 1.29.

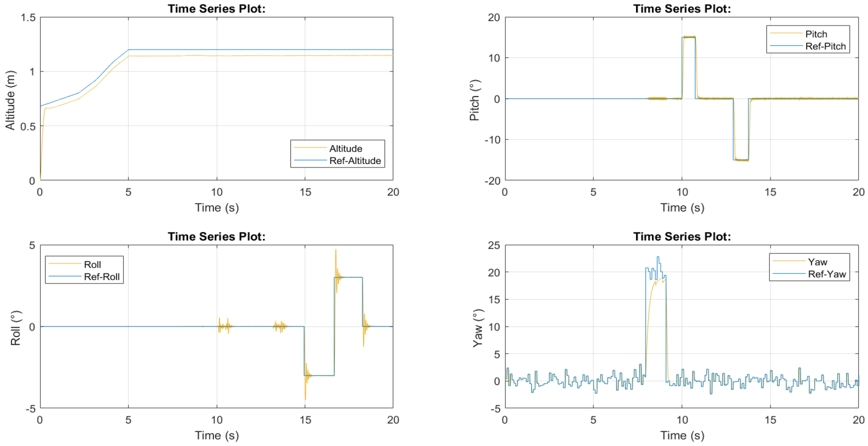

Figure 1.29: Yaw input sensor errors

- Output sensor errors

For altitude sensor output fault: We notice that unlike when the fault was in the input sensor, the reference signal of the altitude display remains unchanged. In the Figure.1.30, it is evident that the output trajectories of altitude, yaw, pitch, and roll approximately track the reference signal, albeit with significant oscillations in the outputs.

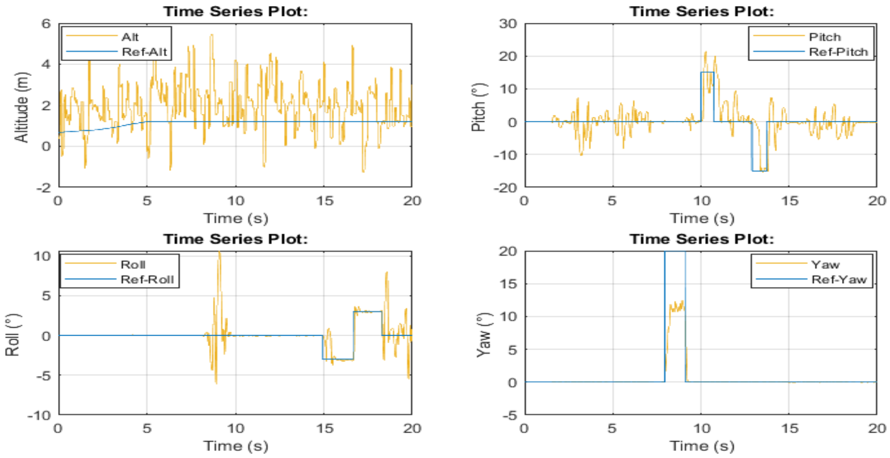

Figure 1.30: Altitude output sensor errors

For a pitch sensor output fault: We observe that the reference signal for pitch remains unchanged. The trajectories of altitude, pitch, roll, and yaw outputs closely follow their respective references, albeit with significant oscillations in pitch and some oscillations in the roll output.

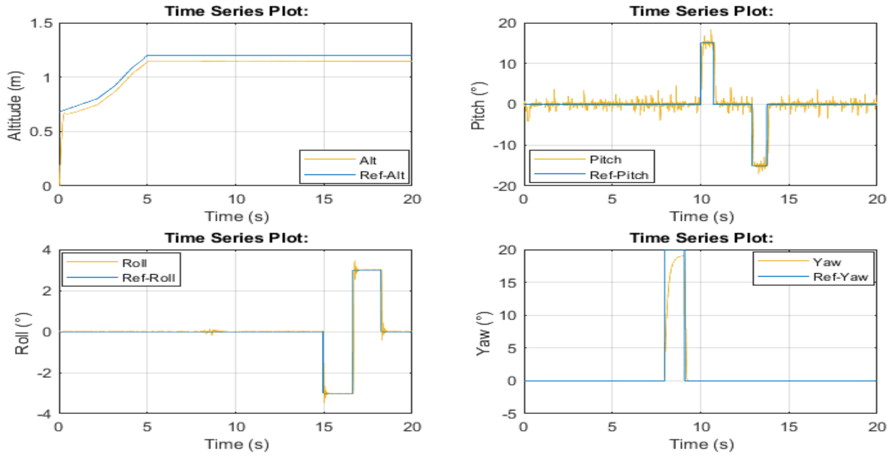

Figure 1.31: Pitch output sensor errors

For a roll sensor output fault: We note that the reference signal for roll remains constant. The trajectories of altitude, pitch, roll, and yaw outputs closely track their respective references, although there are considerable oscillations in the roll output and some oscillations in the pitch output.

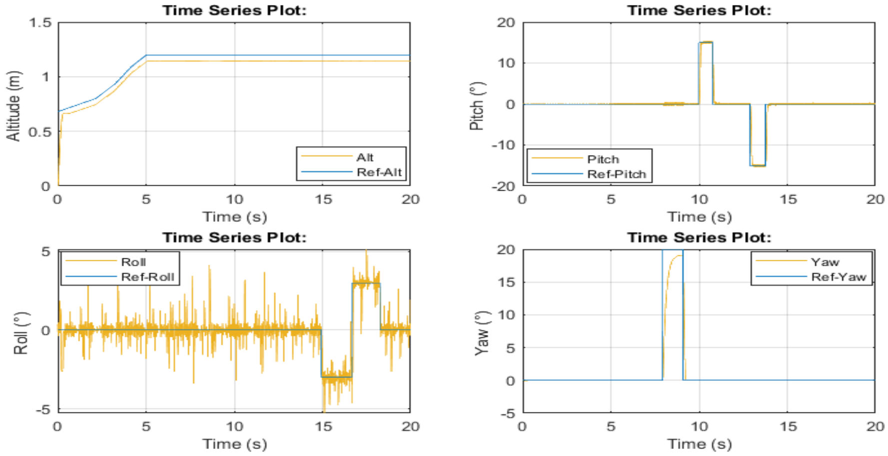

Figure 1.32: Roll output sensor errors

For a yaw sensor output fault: We notice that the reference signal for yaw remains consistent. The trajectories of altitude, pitch, roll, and yaw outputs closely follow their respective references, although there are significant oscillations in yaw and some oscillations in the pitch and roll outputs.

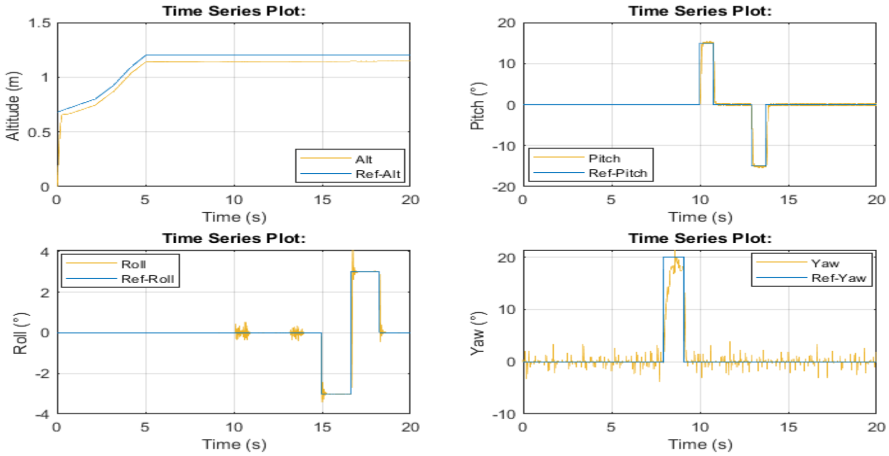

Figure 1.33: Yaw output sensor errors

1.7.5.3 Disturbances

In analyzing the disturbance fault type, a peak appeared in the reference graphs. we notice that despite this disturbance, the outputs remained unaffected.

Results of roll disturbance shown in Figure 1.34.

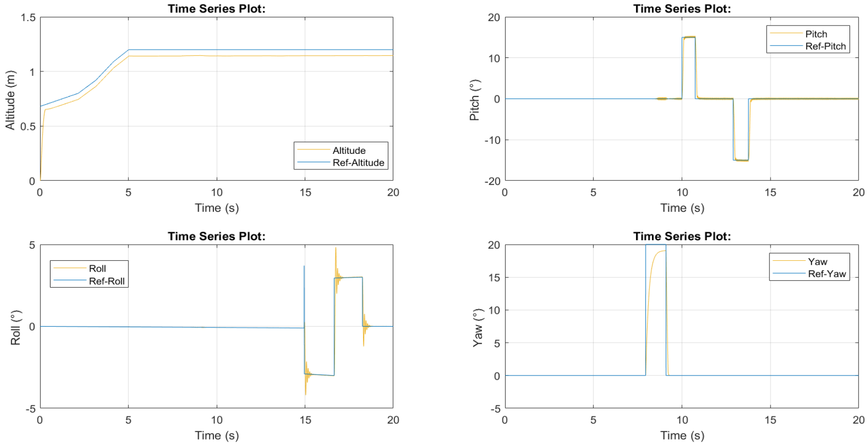

Figure 1.34: Roll disturbance

Results of pitch disturbance shown in Figure 1.35.

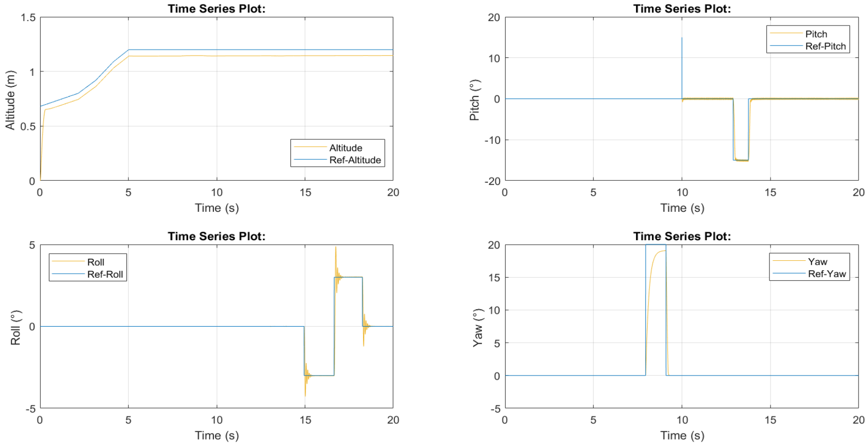

Figure 1.35: Pitch disturbance

Results of yaw disturbance shown in Figure 1.36.

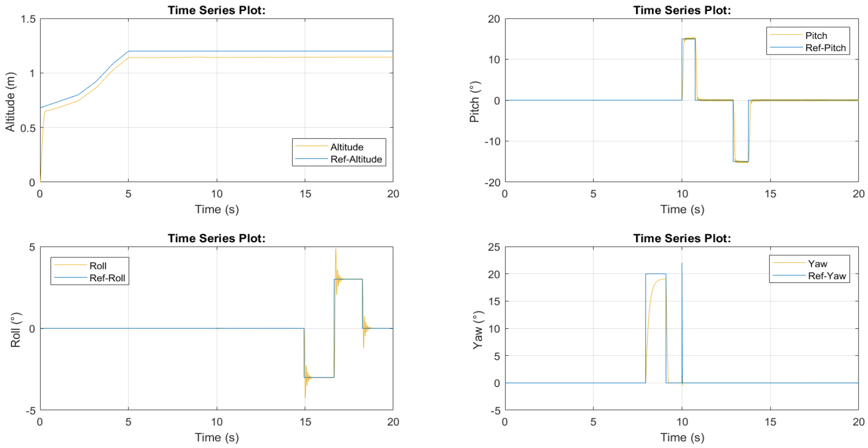

Figure 1.36: Yaw disturbance

1.8 Conclusion

In this chapter, we have outlined the comprehensive approach taken in our study. We began by detailing the controllers utilized in our research, specifically focusing on PID (Proportional-Integral-Derivative) and fuzzy logic controllers, elucidating their fundamental principles. Following this, we proceeded to the modeling of the quadcopter, providing a thorough overview of the mathematical representations involved.

During the simulation phase, we utilized Matlab/Simulink to simulate the quadcopter system with PID controllers, manually adjusting the gains to determine the optimal settings. Similarly, simulations were conducted with fuzzy logic controllers to identify suitable scaling factors. A comparative analysis of the performance of these two controllers was then performed, highlighting their respective strengths and weaknesses. Furthermore, we examined how the system responds to faults, providing insights into its robustness and reliability.

General Conclusion

This dissertation has investigated the control of quadcopters using both PID and Fuzzy PID controllers, with a special focus on fault detection and system robustness. The study provides a comprehensive analysis of these control methodologies and their effectiveness in managing quadcopter dynamics under various conditions. The key conclusions drawn from this research are summarized as follows:

Control System Performance

- The PID controller, known for its simplicity and ease of implementation, effectively maintained the stability of the quadcopter under normal operating conditions. However, it exhibited limitations in dealing with non-linearities and disturbances.
- The Fuzzy PID controller, integrating fuzzy logic with traditional PID control, demonstrated superior performance in handling non-linearities and adapting to changing conditions. This adaptability resulted in improved stability and control, particularly in the presence of external disturbances and system faults.

Fault Detection and Management

- Fault detection is critical for the safe and reliable operation of quadcopters. This study examined various fault scenarios, including motor failures, sensor errors, and external disturbances.
- The simulation results highlighted the Fuzzy PID controller's enhanced capability to detect and manage faults compared to the traditional PID controller. The fuzzy logic component allowed for better handling of unexpected changes and maintaining control despite faults.

Simulation and Analysis

- Extensive simulations conducted in MATLAB/Simulink provided a detailed comparison of the two control strategies. The results confirmed that while both controllers can stabilize a quadcopter, the Fuzzy PID controller consistently outperformed the PID controller in terms of faster response times, reduced oscillations, and better fault tolerance.
- The Fuzzy PID controller's performance was particularly notable in scenarios involving significant disturbances or component failures, showcasing its robustness and reliability.

Practical Implications

- The findings of this research have significant practical implications for the design and implementation of control systems in UAVs. The improved adaptability and fault tolerance of the Fuzzy PID controller make it a viable option for enhancing the reliability and efficiency of quadcopters, especially in applications requiring high stability and precision.

The implementation of Fuzzy PID control systems can enhance the operational capabilities of quadcopters in various fields, including delivery services, surveillance, and environmental monitoring.

Future Work

- Future research should focus on the real-world application and validation of the Fuzzy PID controller in different environmental conditions and with various UAV models. This will help to address any practical challenges and refine the control algorithms further.

- Exploring advanced fault detection and recovery algorithms in combination with Fuzzy PID controllers can provide additional layers of reliability and robustness. Additionally, the integration of machine learning techniques with fuzzy logic could further enhance the adaptability and performance of quadcopter control systems.

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