UNIVERSITY OF THESSALY

DEPARMENT OF MECHANICAL ENGINEERING

DESIGNING A CONTROL SYSTEM FOR A QUADCOPTER

by

Stelios Andriotis

Diploma Thesis

Submitted to fulfill part of the requirements for

obtaining the Diploma in Mechanical Engineering

Volos, 2023

UNIVERSITY OF THESSALY

DEPARMENT OF MECHANICAL ENGINEERING

DESIGNING A CONTROL SYSTEM FOR A QUADCOPTER

by

Stelios Andriotis

Diploma Thesis

Submitted to fulfill part of the requirements for

obtaining the Diploma in Mechanical Engineering

Volos, 2023

ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΙΑΣ
ΠΟΛΥΤΕΧΝΙΚΗ ΣΧΟΛΗ
ΤΜΗΜΑ ΜΗΧΑΝΟΛΟΓΩΝ ΜΗΧΑΝΙΚΩΝ

ΣΧΕΔΙΑΣΜΟΣ ΕΛΕΓΚΤΗ ΘΕΣΗΣ ΕΝΟΣ ΤΕΤΡΑΚΟΠΤΕΡΟΥ

υπό

Στυλιανού Ανδριώτη

Διπλωματική Εργασία

Υπεβλήθη για την εκπλήρωση μέρους των απαιτήσεων για
την απόκτηση του Διπλώματος Μηχανολόγου Μηχανικού

Βόλος, 2023

Εγκρίθηκε από τα Μέλη της Τριμελούς Εξεταστικής Επιτροπής:

Πρώτος Εξεταστής (Επιβλέπων)	Δρ. Κωσταντίνος Αμπουντώλας Καθηγητής, Τμήμα Μηχανολόγων Μηχανικών, Πανεπιστήμιο Θεσσαλίας
Δεύτερος Εξεταστής	Δρ. Δημήτριος Παντελής Καθηγητής, Τμήμα Μηχανολόγων Μηχανικών, Πανεπιστήμιο Θεσσαλίας
Τρίτος Εξεταστής	Δρ. Αναστάσιος Σταματέλλος Καθηγητής, Τμήμα Μηχανολόγων Μηχανικών, Πανεπιστήμιο Θεσσαλίας

DESIGNING A CONTROL SYSTEM FOR A QUADCOPTER

STELIOS ANDRIOTIS

Department of Mechanical Engineering, University of Thessaly, 2023

Supervisor: Ampountolas Kostantinos
Associate Professor

Abstract

This thesis is dedicated to the control design of a quadcopter, specifically the Parrot Mambo case, with an emphasis on the improvement of stability, performance, and reliability. The primary objective of this research was to develop a comprehensive control system using Simulink for the quadcopter to enable autonomous navigation while simultaneously maintaining a high degree of stability. The study commences with the presentation of a model designed for simple hovering maneuvers and subsequently extends to encompass a detailed position control design.

Within the scope of this research, the dynamic and kinematic equations governing the quadcopter's behavior are expounded. These equations are implemented in the Simulink environment, serving as the foundational framework to achieve the objectives set forth in this thesis. To facilitate the control of the quadcopter, Proportional-Integral-Derivative (PID) controllers have been judiciously employed and meticulously tuned. This utilization of PID controllers is pivotal in optimizing the control system, thereby ensuring the drone's performance adheres to the desired specifications.

Furthermore, the results of the model design are meticulously presented, inclusive of graphical representations. These results focus on the minimal deviation of the quadcopter's behavior from the predefined reference points in space.

The conducted research endeavors to enhance the control and autonomy of quadcopters, addressing key aspects of stability and performance. By providing a comprehensive model design and employing PID controllers, this thesis contributes to the advancement of drone technology and autonomous navigation systems.

Key words: Coordinate Systems, Euler Angles, Transformation Matrix, State Variables, Control System Inputs, Translational Motion, Rotational Motion, Controlled Plant, Proportional-Integral-Derivative Controller.

ΣΧΕΔΙΑΣΜΟΣ ΕΛΕΓΚΤΗ ΘΕΣΗΣ ΕΝΟΣ ΤΕΤΡΑΚΟΠΤΕΡΟΥ

ΣΤΥΛΙΑΝΟΣ ΑΝΔΡΙΩΤΗΣ

Τμήμα Μηχανολόγων Μηχανικών, Πανεπιστήμιο Θεσσαλίας, 2023

Επιβλέπων Καθηγητής: Αμπουντώλας Κωσταντίνος
Αναπληρωτής Καθηγητής

Περίληψη

Αυτή η διατριβή ασχολείται με τον σχεδιασμό ενός μοντέλου, ελέγχου ενός τετρακόπτερου, στην ειδική περίπτωση του Parrot Mambo, με έμφαση στη βελτίωση της σταθερότητας, της απόδοσης και της αξιοπιστίας του. Ο κύριος στόχος αυτής της έρευνας ήταν η ανάπτυξη ενός συστήματος ελέγχου χρησιμοποιώντας το λογισμικό Simulink, προκειμένου να επιτευχθεί η αυτόνομη πλοήγηση του Drone , διατηρώντας ταυτόχρονα υψηλό επίπεδο σταθερότητας. Η μελέτη ξεκινά με την παρουσίαση ενός μοντέλου που σχεδιάστηκε για απλή αιώρηση και επεκτείνεται στη συνέχεια σε μια λεπτομερή σχεδίαση ελέγχου θέσης στο χώρο.

Εντός του πλαισίου αυτής της έρευνας, αναπτύσσονται οι δυναμικές και κινηματικές εξισώσεις που διέπουν τη συμπεριφορά του τετρακόπτερου. Αυτές οι εξισώσεις εφαρμόζονται στο περιβάλλον του Simulink και λειτουργούν ως το θεμελιώδες πλαίσιο για την επίτευξη των στόχων που τέθηκαν σε αυτήν την έρευνα. Για τη διευκόλυνση του ελέγχου του τετρακόπτερου, χρησιμοποιούνται ελεγκτές τύπου PID (Proportional-Integral-Derivative. Η χρήση αυτών των ελεγκτών είναι καίρια για την βελτιστοποίηση του συστήματος ελέγχου, εξασφαλίζοντας έτσι ότι η απόδοση του τετρακόπτερου πληροί τις επιθυμητές προδιαγραφές.

Επιπλέον, παρουσιάζονται λεπτομερώς τα αποτελέσματα του μοντέλου, συμπεριλαμβανομένων γραφικών αναπαραστάσεων. Αυτά τα αποτελέσματα επικεντρώνονται στην ελάχιστη απόκλιση της συμπεριφοράς του τετρακόπτερου από τα προκαθορισμένα σημεία αναφοράς στο χώρο.

Η διεξαγόμενη έρευνα προσπαθεί να ενισχύσει τον έλεγχο και την αυτονομία των τετρακόπτερων, επικεντρώνοντας σε καίριες πτυχές όπως η σταθερότητα και η απόδοση. Παρέχοντας έναν σφαιρικό μοντέλο σχεδίασης και χρησιμοποιώντας ελεγκτές PID, αυτή η έρευνα συμβάλλει στην προαγωγή της τεχνολογίας των τετρακόπτερων και των συστημάτων αυτόνομης πλοήγησης.

Nomenclature

PID: Proportional-Integral-Derivative

UAV: Unmanned Aerial Vehicle

DOF: Degrees of Freedom

NED: North-East-Down

EF: Earth-Fixed

CG: Center of Gravity

LQR: Linear Quadratic Regulator

MPC: Model Predictive Control

SLAM: Simultaneous Localization and Mapping

Table of contents

List of Figures

List of Tables

1.Introduction

1.1 Thesis Objective

This thesis is dedicated to achieving a fundamental understanding of control systems theory in conjunction with a comprehensive exploration of the dynamic and kinematic equations governing drone motion within three-dimensional space. Furthermore, the utilization of Simulink as a powerful simulation tool is employed to breathe life into these theoretical underpinnings, allowing for safe and controlled experimentation without exposing the drone to real-world risks. In doing so, this research endeavors to bridge the gap between theoretical concepts and practical implementation, all while mitigating the inherent risks associated with real-world experimentation.

1.2 Literature Review

The dynamic field of drone technology has experienced a significant transformation, evolving from its origins in military applications to its current status as a versatile tool with a wide range of practical applications. From improving their performance with lighter materials and better butteries, to better control methods and mapping algorithms.

This literature review centers on UAV control methods, with a focus on trajectory guidance and SLAM (Simultaneous Localization and Mapping) technology. The domain of UAVs has seen the application of several control methods to navigate and manipulate these aerial systems. Within the framework of this thesis, PID (Proportional-Integral-Derivative) control is employed as the primary control method to achieve the overarching objective of precise position control. However, it is imperative to acknowledge that tuning PID parameters poses inherent challenges, particularly in the presence of external disturbances, which are commonplace in real-world scenarios.

In response to these challenges, more advanced control methodologies, including Linear Quadratic Regulator (LQR), Model Predictive Control (MPC), and Robust Control, have emerged as potent alternatives. These advanced control approaches exhibit heightened efficacy, especially when dealing with systems susceptible to disturbances.

Notably, comparative evaluations reveal distinct advantages in tracking trajectory with LQR control, characterized by its capacity to produce smoother trajectory paths compared to the traditional PID controller [7],[20]. Furthermore, MPC stands out as the most advanced and capable control method, consistently yielding superior outcomes in terms of trajectory tracking precision and robustness. This forward-thinking approach has witnessed further refinements, exemplified by variants such as Linear Model Predictive Control (LMPC) and Nonlinear MPC (NMPC), each offering unique advantages for achieving precise trajectory control in UAV systems [17]. Also, research on adaptive position controller based on Model Predictive Control is explored for quadrotors, leveraging adaptation mechanisms to enhance performance and adapt to changing operating conditions [16]. These developments collectively underscore the progression of control methods in the UAV domain, signifying their increasing effectiveness in addressing the multifaceted challenges posed by real-world environments.

Furthermore, in the realm of autonomous operations, a fundamental requirement for a drone is the ability to understand its environment and be able to localize itself within it. This imperative task is encapsulated within the purview of Simultaneous Localization and Mapping (SLAM), a longstanding and actively researched domain within the field of robotics over the course of the past three decades. The initial stages of research in this area were largely dedicated to the complexities surrounding state estimation in SLAM, encompassing a diverse array of pose estimation algorithms, notably reliant on Extended Kalman Filter (EKF), Unscented Kalman Filter (UKF), and Particle Filter (PF) methodologies [3]. It is intriguing to note that this body of research has not been confined to SLAM algorithm development alone. In parallel, there has been a pronounced emphasis on advancements in sensor technology.[18]

Over the intervening decades, SLAM's trajectory has been one of exponential evolution. It remains an active arena for enhancing the precision, estimation, and error rate reduction qualities intrinsic to SLAM algorithms. This trajectory of evolution is punctuated by notable milestones; in 2002, the introduction of the FastSLAM algorithm marked a significant breakthrough, while in 2006, the proposal of a smoothing method named Square Root Smoothing and Mapping (SAM) further expanded the horizons of SLAM capabilities [2].

As drone applications diversify into delivery, surveillance, and autonomous transport, future technologies are steering towards advanced control methods. Emerging approaches, including Reinforcement Learning and AI-based control, leverage machine learning and neural networks, allowing drones to adapt in real-time. This promises more precise trajectory control and enhanced environmental navigation, opening doors to applications like disaster response and urban transport with a focus on safety and precision [22].

2. Drones: An In-Depth Overview

2.1 Brief history of UAVs

Unmanned aerial vehicles (UAVs) are aircraft with no on-board crew or passengers. They can be automated "drones" or remotely piloted vehicles (RPVs). The development of the first pilotless aircraft began in the early 20th century.

Figure 1. The Aerial Target, a British radio-controlled aircraft from the First

During the First World War, Britain and the USA developed the first pilotless aircraft. The American aerial torpedo known as the Kettering Bug (the first drone ever made) made its first flight in October 1918, while the British Aerial Target (the first recognized drone), a small radio-controlled aircraft, was tested for the first time in March 1917. Although both seemed promising during flying tests, neither was actually put into action during the war.

In 1935 the British produced a few radio-controlled aircraft to be used as targets for training purposes. One of these models was the DH.82B Queen Bee. It's believed the term 'drone' started to be used at this time, inspired by this model's name. [10]

Figure 2. Launch of a De Havilland Queen Bee seaplane from its ramp.

Drone technology has advanced quickly, and both their usability and accessibility have grown over time. In 2006 drones were finally allowed to be used for recreational purposes, and they were no longer just for military use. In 2010, the French technology company Parrot launched the AR. Drone, a major turning point for quadcopters. This revolutionary invention was the first consumer drone that was mostly operated via a smartphone or tablet. It expanded drone recreational use and raised public interest in them.

2.2 Applications

Drones have developed quickly despite the fact that they initially designed for military use. Individual business owners and large companies use drones today for a variety of different jobs. Some of the applications are presented below:

- Aerial photography for journalism and film:

Drones provide plenty of advantages when it comes to capturing aerial pictures and B-roll for films. They offer countless new options to take high-quality photos and videos, including perspectives that were either impossible or extremely challenging to achieve in the past. In comparison to crane shots, they are far simpler to use and set up, and they are significantly less expensive than employing a camera crew for a helicopter. For this reason, it is believed drone-based picture and filming is the future.

- Express shipping and delivery:

Worldwide, more than 2,000 commercial drone deliveries took place per day from the beginning of 2022 and that number has only grown since. Even if this number is still small compared to the overall number of commercial deliveries, it shows that current activity extends beyond test flights. Drone technology has the ability to satisfy demands such as transporting medical samples to laboratories, as well as a variety of last-mile consumer use cases, such as prepared meals, convenience goods, and other compact packages.

- Building safety inspections:

Drones can be used in construction to inspect the quality, structural integrity, and progress of buildings, bridges, roads etc. In the energy industry, they can evaluate the effectiveness and operation of networks and power plants and check for pipeline leaks or damage without exposing workers to danger.

- Collecting data or providing essentials for disaster management and rescue activities:

The drones are able to quickly reach the area where disasters have occurred. Before rescue teams get there, they collect information about what happened, the damage that has been done, and whether there are victims that need to be rescued. Additionally, due to their mobility, drones can get into and investigate risky places and collect data more effectively and precisely than using traditional methods, allowing researchers to carefully examine the data.

- Entertainment:

Although many UAVs are built for specific purposes, many other drones are used for fun. Several examples include recording personal films and photos, for drone competitions and racing or even for fishing.

2.3 Parrot Mini-Drone case, Hardware overview

The primary objective of this thesis is fundamentally applicable to a broad spectrum of drone platforms. However, for the purposes of this research, the Parrot Mambo drone has been specifically selected as a representative case study. This choice is made in order to facilitate a comprehensive examination of the theoretical framework in a real-world context, allowing for a more in-depth exploration and analysis of the research objectives and their practical implications within the specific context of the Parrot Mambo drone platform.

Firstly, when we use the term "quadcopter", we refer to a four-rotor unmanned aerial vehicle. Parrot drones are a brand of consumer-grade unmanned aerial vehicles (UAVs) manufactured by Parrot SA. The components of a Parrot drone may vary depending on the specific model and its intended purpose. The usual components are the following: Quadcopter Frame, Motors and Propellers, a Lithium-polymer (LiPo) Battery, a Flight Controller which is the drone's brain, responsible for stabilizing the aircraft, managing its orientation, and processing user inputs from the remote controller or smartphone app. In addition, Parrot drones often come equipped with various sensors, such as:

- Accelerometers: Measure acceleration and help maintain stability.
- Gyroscopes: Measure angular velocity and assist in maintaining balance.
- Magnetometers: Determine the drone's orientation with respect to Earth's magnetic field.
- Ultrasound Sensors: Aid in altitude control by measuring distance to the ground.

2.4 Basic quadcopter modeling and control concept.

The architecture of the quadcopter's control system is a closed-loop feedback design, consisting of three main components: the controller, the plant, and the sensors. The controller is the central component of the system that processes data from sensors and generates commands for the motors to maintain stability and control flight. The "plant" in the context of a drone's control system refers to the set of mathematical equations that model and describe the physical behavior of the drone, including its motion, dynamics, and response to control inputs. Lastly, sensors provide essential real-time data for navigation and stability.

Close-loop feedback control for a drone involves a continuous cycle of sensor data collection (from accelerometers, gyroscopes, etc.) and error calculation based on the desired flight parameters set by the flight controller (input). The error, representing the difference between desired and actual states (e.g., altitude, position), guides the generation of control signals that adjust the drone's motors and propellers in real-time. These adjustments allow the drone to correct any deviations, maintain stability, and achieve precise flight. The drone can adapt swiftly to changes thanks to this feedback loop, which runs at a high frequency and eventually provides a steady controlled flight experience. In simple terms, a close-loop feedback control for a drone means it uses sensors to constantly check how it's doing, make corrections to stay on course, and fly steadily and accurately.

In the pursuit of simplifying the modeling process, this thesis opts not to incorporate external sensors into the model, electing instead to focus on the theoretical foundations of control systems and their application in drone dynamics. This approach emphasizes a theoretical exploration of control methodologies and their impact on the drone's behavior within a simulated environment.

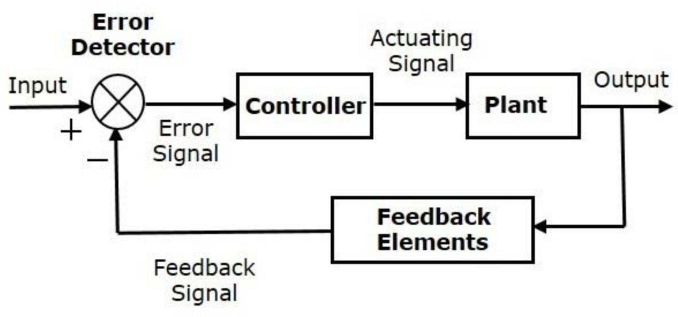


Figure 3. Closed-loop feedback design.

3.Modeling Drone Behavior

3.1 Six-degrees of freedom (6-DOF)

In this chapter the flight dynamics model will be developed. In order to mathematically represent the motion of the quadcopter, the concept of 6-degrees of freedom (6-DOF), is necessary. 6-DOF concept gives the position and the orientation of the vehicle in three dimensions (3-D). Vehicles dynamic equations simply represent the change in orientation and position over time.

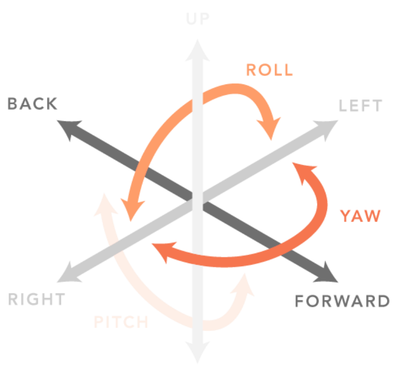


Figure 4. 6-DOF.

3.2 Coordinate systems

To set up the model of the quadcopter, the reference coordinate frames should be defined. The reference frame of the quadcopter will be local North-East-Down (NED). In a NED coordinate system, the X-axis points to the North, the Y-axis points to the East, and the Z-axis points Down, typically used in aviation and navigation. The origin of the NED frame is fixed in, Earth-Fixed frame (EF). The Body-Fixed frame of reference has its origin at the center of gravity of the aircraft, thus it moves with the aircraft itself. The X-axis of the body frame is pointed toward the aircraft, the Y-axis is along the right and Z-axis points down. In the case where the aircraft is not rotated, the body axes have the same orientation as NED axes [5].

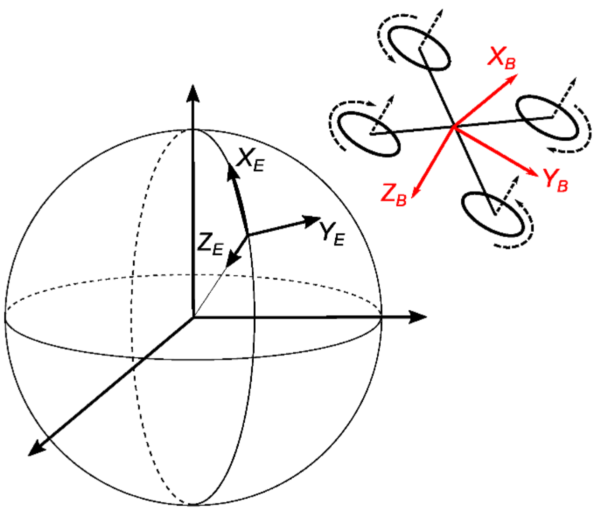


Figure 5. NED Reference Frame located on the earth surface. Body Reference Frame centered in the Center of Gravity of the quadrotor.

3.3 Euler Angles

The orientation or rotation of an object in three dimensions, with respect to a fixed coordinate system, is described by a set of three rotational angles known as Euler angles, which are typically referred to as pitch (θ-theta), yaw (ψ-psi) and roll (ϕ-phi). In the NED coordinate system, with positive roll angles the quadcopter travels east, with positive pitching angles the quadcopter travels south and with positive yaw angles the quadcopter rotates clockwise. To establish a connection between these coordinate systems (Earth-fixed and Body-fixed), it is necessary to construct a transformation matrix. Defining this transformation matrix relies on the crucial utilization of Euler angles. Specifically, it involves executing three sequential rotations: yaw around the Z-axis, pitch around the Y-axis, and lastly, roll around the X-axis. Euler angles provide a powerful mathematical framework for describing the orientation of drones in three-dimensional space.

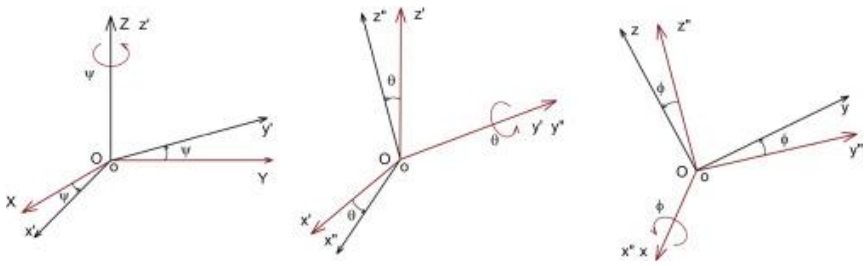


Figure 6. The three rotations: yaw around the Z-axis, pitch around the Y-axis, and lastly, roll around the X-axis.

3.4 Transformation Matrix

Initially, rotation matrices along each axis are presented:

- Rotation about the X-axis (Roll, ϕ):

$$R_x(\varphi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\varphi & sin\varphi \\ 0 & -sin\varphi & cos\varphi \end{bmatrix} \tag{3.1}$$

- Rotation about the Y-axis (Pitch, θ):

$$R_y(\theta) = \begin{bmatrix} cos\theta & 0 & -sin\theta \\ 0 & 1 & 0 \\ sin\theta & 0 & cos\theta \end{bmatrix} \tag{3.2}$$

- Rotation about the Z-axis (Yaw, ψ):

$$R_z(\psi) = \begin{bmatrix} cos\psi & sin\psi & 0 \\ -sin\psi & cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3.3}$$

To obtain the transformation matrix from the body frame to the NED frame, you multiply these matrices in the ZYX order:

$$R_{BE} = R_z(\psi) \cdot R_y(\theta) \cdot R_x(\varphi) =$$

$$\begin{bmatrix} cos\theta cos\psi & sin\psi cos\varphi + cos\psi sin\theta sin\varphi & sin\psi sin\varphi - sin\theta cos\psi cos\varphi \\ -sin\psi cos\theta & cos\varphi \cdot cos\psi - sin\theta sin\psi sin\varphi & cos\psi sin\varphi + sin\theta sin\psi cos\varphi \\ sin\theta & -cos\theta sin\varphi & cos\theta cos\varphi \end{bmatrix} \tag{3.4}$$

This rotation matrix will be used to convert the states measured in one frame to another frame.

3.5 Dynamic Model

This chapter delves into the derivation and application of the dynamic equations governing drone motion. These equations reveal the intricate link between translation (x, y positions, and altitude) and rotation (roll, pitch, and yaw). By elucidating these fundamental principles, a deeper understanding of how drones navigate in three-dimensional space and respond to external influences is achieved. This knowledge serves as the foundation for the development of advanced control algorithms, enabling precise and efficient drone operations. In the following sections, an exploration of the formulation of these dynamic equations is conducted, taking into account the forces and moments acting on the drone, and elucidating their roles in controlling both translation and rotation. It is assumed that the quadcopter's structure is rigid and symmetrical around its center of gravity. Here, the translation motion of the quadcopter is described by the Newton-Euler Equation:

$$\vec{F} = \frac{d}{dt}(m \cdot \vec{u}) \tag{3.5}$$

Where $\vec{F} = \vec{G} - \overrightarrow{F_z}$, G is the gravity and F_z is the thrust generated from the rotors. The F_z is described in the body frame and must be transformed from body frame to inertial frame. Equation X can therefore be written as:

$$m \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ mg \end{bmatrix} - R_{BE} \begin{bmatrix} 0 \\ 0 \\ F_z \end{bmatrix} \tag{3.6}$$

This vector equation can be written in component form as:

$$\ddot{x} = -\frac{1}{m}[F_z(sin\varphi sin\psi + cos\varphi cos\psi sin\theta) \tag{3.7}$$

$$\ddot{y} = \frac{1}{m}[F_z(sin\varphi cos\psi - sin\theta cos\varphi sin\psi)] \tag{3.8}$$

$$\ddot{z} = g - \frac{F_z}{m}(cos\theta cos\varphi) \tag{3.9}$$

3.6 Thrust Force and Moments

The quadcopter's propellers provide thrust that acts perpendicular to the vehicle and moment that acts at the vehicle's center of gravity. The distance between the vehicle's center of gravity (CG) and the propellers is depicted in Figure 7.

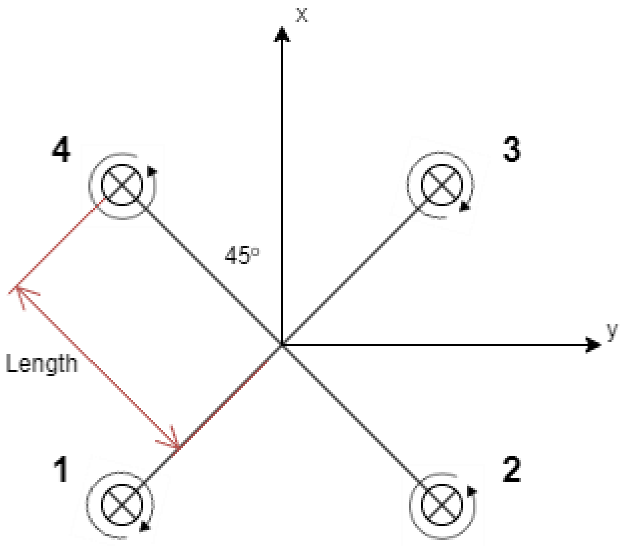


Figure 7. Drone’s top view-X frame.

To simplify the process of designing a stabilizing controller, an actuator decoupling matrix is usually chosen based on the frame's configuration. In the case of the Parrot Mambo 'X' drone frame, the matrix mentioned in equation (3.4) associates the four squared speed references ($\Omega^2{}_1$, $\Omega^2{}_2$, $\Omega^2{}_3$, and $\Omega^2{}_4$) with the generation of lift force and stabilizing torques. In control theory, a decoupling matrix simplifies multivariable system control by untangling variable interdependencies. It helps isolate each variable for independent control, allowing the design of controllers that achieve desired actions without significantly impacting other variables. For instance, in a control system that does not employ an actuator decoupling matrix, when a robot requires forward motion (translation), it necessitates the simultaneous application of input to both wheel actuators, which can prove challenging to synchronize.

$$\begin{bmatrix} F_z \\ L \\ M \\ N \end{bmatrix} = \begin{bmatrix} -k_f & -k_f & -k_f & -k_f \\ \frac{l}{\sqrt{2}}k_f & -\frac{l}{\sqrt{2}}k_f & -\frac{l}{\sqrt{2}}k_f & \frac{l}{\sqrt{2}}k_f \\ -\frac{l}{\sqrt{2}}k_f & -\frac{l}{\sqrt{2}}k_f & \frac{l}{\sqrt{2}}k_f & \frac{l}{\sqrt{2}}k_f \\ K_m & -K_m & K_m & -K_m \end{bmatrix} \cdot \begin{bmatrix} \Omega_1^2 \\ \Omega_2^2 \\ \Omega_3^2 \\ \Omega_4^2 \end{bmatrix} \tag{3.10}$$

In that matrix also, L is roll torque, M is pitch torque and N is yaw torque. Also, K_f is thrust coefficient and K_m is the drag coefficient and l is the length of the lever.

The four rotor rotational speeds, Ω_i, represent the real vehicle's input variables, and the transformation aligns appropriately with the established model. An additional variable must be considered, which it depends on the rotational speeds of rotors. Thus, it must be considered as the fifth artificial input:

$$\Omega_r = \Omega_1 - \Omega_2 + \Omega_3 - \Omega_4 \tag{3.11}$$

Two propellers rotate clockwise and other two rotate counter-clockwise to balance the yaw moment.

3.7 Kinematics

The rotational dynamics are described as [4]:

$$I\ddot{\eta} = -\dot{\eta} \times I\dot{\eta} - \sum_{i=1}^{4} J_r \left(\dot{\eta} \times \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \right) \Omega_i + \tau \tag{3.12}$$

where I is the inertia matrix:

$$I = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \tag{3.13}$$

Also, J_r is the inertia of the rotor, the vector $\tau = [L\ M\ N]^T$ expresses the torque, which is applied to the body frame, and $\eta = [\varphi\ \theta\ \psi]^T$ expresses the vector of Euler. So, a second set of differential equations is obtained:

$$I_{xx}\ddot{\varphi} = (I_{yy} - I_{zz})\dot{\psi}\dot{\theta} - (J_r\Omega_d)\dot{\theta} + lL \tag{3.14}$$

$$I_{yy}\ddot{\theta} = (I_{zz} - I_{xx})\dot{\psi}\dot{\varphi} + (J_r\Omega_d)\dot{\varphi} + lM \tag{3.15}$$

$$I_{zz}\ddot{\psi} = (I_{xx} - I_{yy})\dot{\varphi}\dot{\theta} + N \,, \tag{3.16}$$

where $\Omega_d = \Omega_1 - \Omega_2 + \Omega_3 - \Omega_4$.

Equations involving rotor inertia (J_r) in drone rotation are simplified, practical models derived from rotational principles. They're not fundamental laws but simplifications for easier modeling. They're used as initial designs in control systems but may need further adjustments and testing for real-world use.

An alternative method involves employing the measured angular velocity $\omega = [p\ q\ r]^T$. To achieve this, an additional transformation matrix R_r is required to depict how Euler rates correlate with the quadcopter's angular velocity vector, $\dot{\eta} = R_r \omega$:

$$\begin{bmatrix} \dot{\varphi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & sin\varphi tan\theta & cos\varphi tan\theta \\ 0 & cos\psi & -sin\varphi \\ 0 & \frac{sin\varphi}{cos\theta} & \frac{cos\varphi}{cos\theta} \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{3.17}$$

Using angular rates (p, q, r) is more realistic for simulating drone rotational dynamics. These rates directly depict the drone's body-centered angular speeds, providing a precise model. However, this approach adds complexity, requiring consideration of motor dynamics, aerodynamics, and sensor noise for a complete drone model.

Table 1. Drone's parameters.

Specifications	Parameter	Value	Unit
Quadrotor mass	m	0.0680	Kg
Length of an arm	l	0.0624	m
Thrust coefficient	k_f	0.0107	Ns^2
Drag coefficient	K_m	0.7826400×10^{-3}	Nms^2
Rolling moment of inertia	I_{xx}	0.0582857×10^{-3}	Kgm^2
Pitching moment of inertia	I_{yy}	0.0716914×10^{-3}	Kgm^2
Yawing moment of inertia	I_{zz}	0.1000000×10^{-3}	Kgm^2
Rotor moment of inertia	J_r	0.1021×10^{-6}	Kgm^2

4.State space

4.1 Quadrotor State Space Representation

In control systems, state space is a key concept. It's a mathematical framework used to describe dynamic system behavior, making it easier to model, analyze, and control complex systems. State space representation simplifies the understanding of a system's variables and their relationships, making it a vital tool in control theory and practical applications.

In the case of a drone model, the number of state variables, or state vectors, depends on the level of detail and complexity desired for the model. In general terms a simplified state-space representation of a drone typically comprises six state variables. These state variables describe the drone's position and orientation within a three-dimensional space. They are typically adopted as the primary state variables in the state-space representation of a drone's dynamics.

For more comprehensive and intricate drone models, consideration might be given to the inclusion of state variables associated with:

- Linear velocities along the X, Y, and Z axes
- Angular velocities around the X, Y, and Z axes (commonly denoted as p, q, r).
- Internal states of control systems, such as motor speeds or control inputs.

The choice of state variables hinges on the need for precision and accuracy in drone simulations. For many drone simulations, a straightforward 6-DOF model suffices, while more sophisticated models may incorporate additional states to capture nuanced aspects of the drone's behavior.

The dynamics provided in (3.7) - (3.9) and (3.14) - (3.16) are expressed as a conventional structure of second-order state-space equations:

$$\ddot{x} = f(x) + g(x)u$$

This form of representation is known as a non-linear state-space representation, as the dynamics can be arbitrary functions of the state variables x. It's particularly useful for modeling systems with non-linear behavior. To implement a methodical approach for designing a control system while keeping the notation uncomplicated, we represent the state vector as follows:

$$x = [x_1 \quad x_2 \quad x_3 \quad x_4 \quad x_5 \quad x_6]^T = [x \quad y \quad z \quad \varphi \quad \theta \quad \psi]^T$$

And the input vector is $u = [F_z \quad L \quad M \quad N]$.

5. Simulink Modeling and Control

5.1. Altitude control

In this thesis, the initial objective is to achieve a fundamental maneuver known as a "simple hover" within the realm of drone control. A simple hover represents a critical foundational capability for drones, where the focus lies in maintaining a stable and stationary position in the air. To attain this goal, specific values are assigned to the drone's control inputs. The altitude setpoint is held constant to ensure the drone maintains a fixed vertical position above the ground or a reference point, thereby emphasizing the precise control of altitude. In addition, both horizontal positions along the x and y axes are set to zero (x=0 and y=0), signifying the drone's intention to remain motionless in the horizontal plane. Furthermore, all orientation angles, encompassing roll, pitch, and yaw, are adjusted to zero degrees (ϕ=0, θ=0 and ψ=0), guaranteeing that the drone maintains a level orientation without any rotational movements.

The subsequent research objective involves advancing position control for the drone. Building upon the foundational achievements in stable hovering and orientation control, the focus now shifts to precise three-dimensional positioning. This entails refining control over horizontal positions (x and y) and vertical altitude. The ultimate goal is to enable accurate and controlled navigation, enhancing the drone's utility for applications such as autonomous flight and obstacle avoidance, further expanding its operational capabilities.

5.1.1 Basic Simulink Plant Model

The Simulink plant model can now be created since the fundamental equations of motion have been produced. The subsystem has 4 inputs (F_z, L, M, N) and 6 outputs (X, Y, Z, roll, pitch, yaw). At this point the model should be looking like below. The sum of rotational speed of the rotors (Ω_r = OmgTotal) is considered as the fifth artificial input.

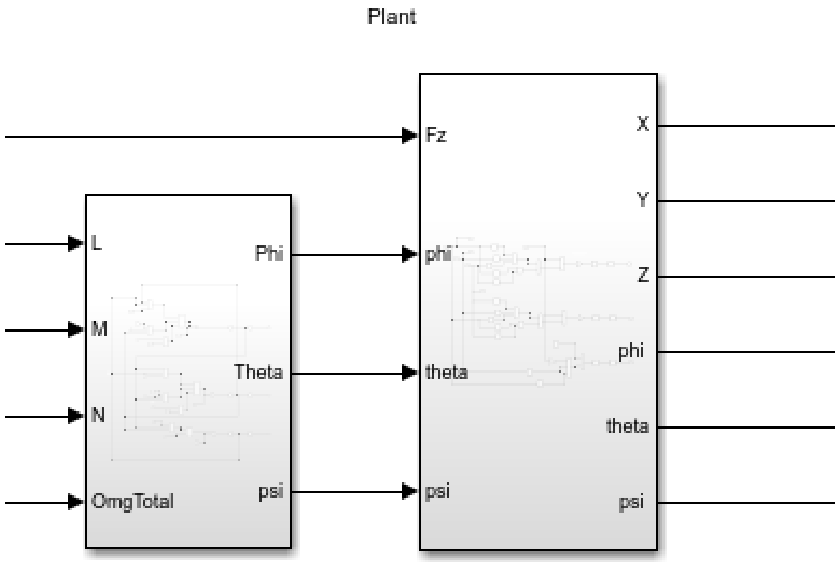


Figure 8. Dynamic Plant.

The initial stage of the procedure involves the application of Equations (3.14 - 3.16) to generate angular accelerations. This computational block accepts inputs of thrust and moments, translating these inputs into the angular accelerations. Following this, a sequence of integration operations is employed, facilitated by specific integration blocks. These integrated processes culminate in the determination of Euler angles. This can be seen in Figure (9).

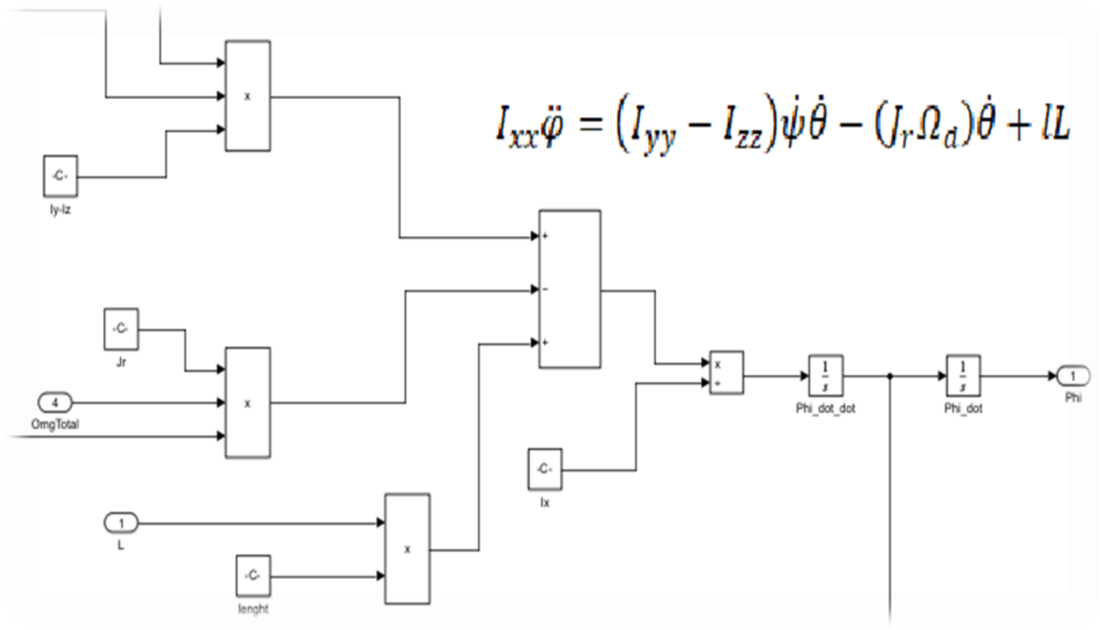


Figure 9. Euler angle phi generation In Simulink.

Following a similar rationale, we proceed to compute the remaining two angles.

The following phase involves the computation of the drone's linear accelerations. Similar to the approach used for angular accelerations, we can establish subsystem blocks for each of the linear accelerations.

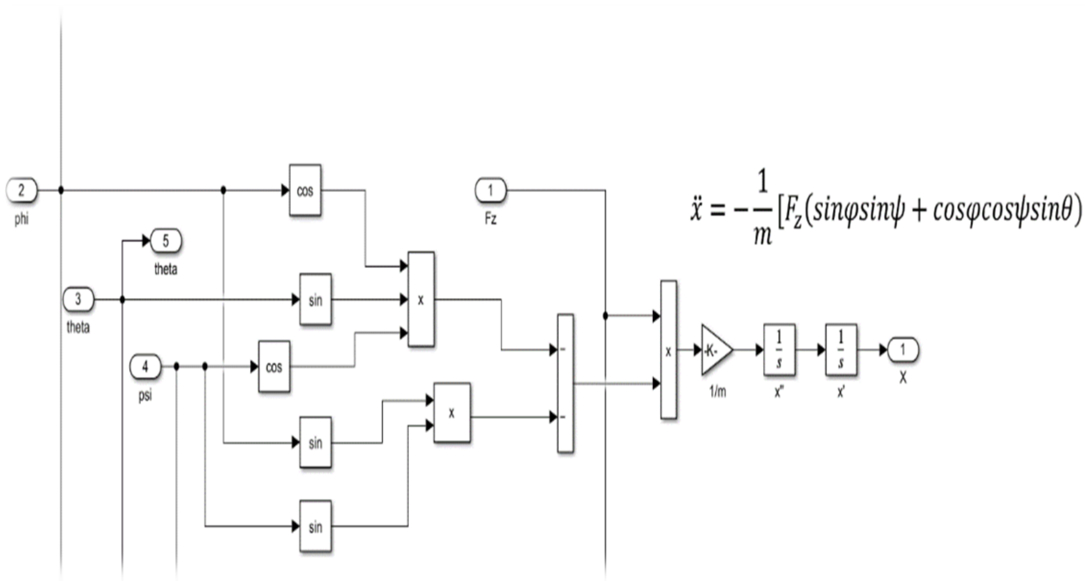


Figure 10. Acceleration on X axis generation in Simulink.

Extending this calculation to the remaining two accelerations, subsequent integration processes give the drone's positional coordinates.

At this stage, we can introduce some inputs to the plant model. Since the plant model deals with rotor speed, we can use a step change to represent the speed of the rotors. This observation is depicted in the subsequent figure (Figure 11). It is noteworthy that in this graphical representation, the Z position is depicted as positive, whereas the model's Z-axis is oriented in a negative direction.

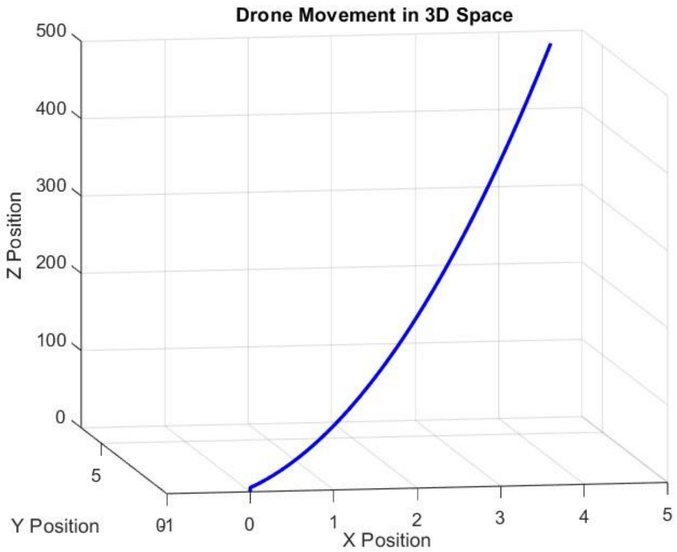


Figure 11. Graphical representation of drone’s movement

5.1.2 Motor Mix Algorithm

The translation of thrust and moments into motor rotation speed is a fundamental process in the dynamics of drones (equations 3.10). This conversion, often likened to the heart of drone control systems, involves the intricate orchestration of forces and torques generated by the rotors. Thrust, acting as the upward force, and moments, representing rotational forces, are judiciously allocated to individual motors, resulting in the precise adjustment of their rotation speeds. Collectively, these individual motor speeds amalgamate to yield the total rotor speed, a pivotal determinant of the drone's flight dynamics. This transformation, akin to a symphony conducted by control algorithms, ensures the drone's equilibrium and responsiveness, allowing it to navigate its environment with stability and precision.

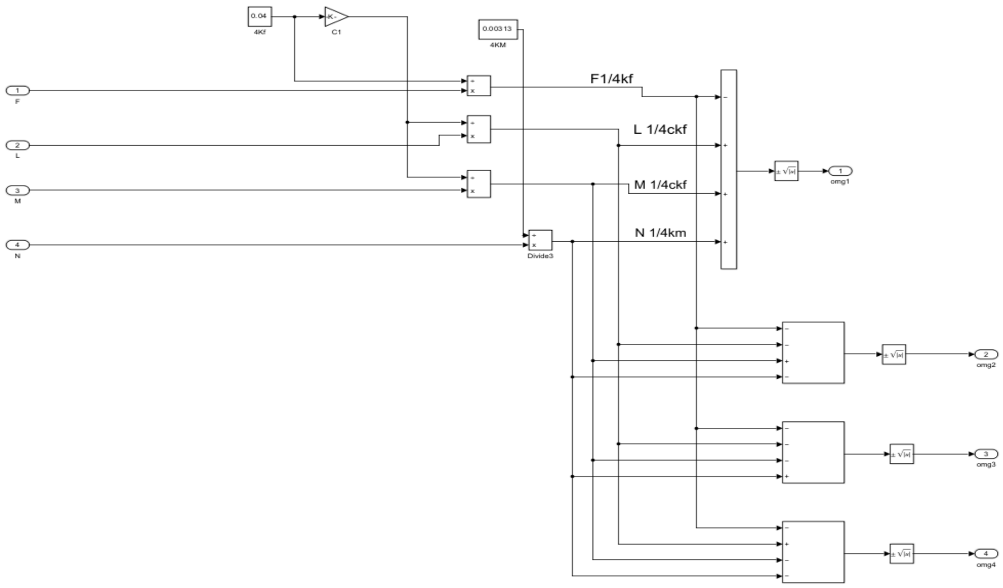


Figure 12. Angular velocity of Motors generation in Simulink

5.1.3 Controller

In the realm of drone control systems, the Proportional-Integral-Derivative (PID) controller emerges as a cornerstone for achieving precision and stability. PID controllers are renowned for their simplicity and effectiveness in regulating a wide array of dynamic systems, including drones. These controllers operate on a straightforward principle: they continuously monitor the error, the difference between the desired setpoint and the current state, and employ a blend of proportional, integral, and derivative terms to compute the control output. The proportional term drives the control action in proportion to the error, the integral term corrects long-term deviations, and the derivative term anticipates future errors by considering the rate of change. This trifecta of control components, when tuned judiciously, empowers PID controllers to respond to dynamic environmental conditions, disturbances, and system uncertainties, thereby enabling drones to maintain precise trajectories, altitude, and orientation. The elegance of PID controllers lies in their adaptability and robustness, rendering them indispensable tools in the realm of drone control and navigation.

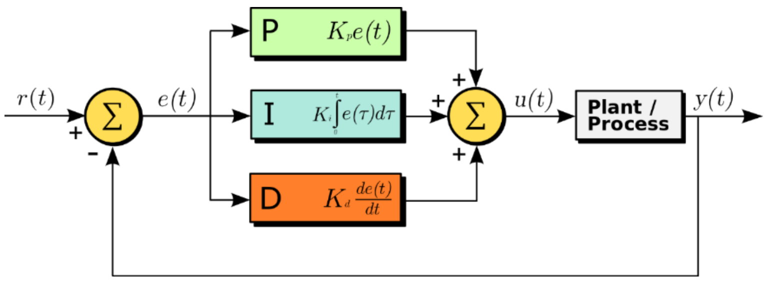


Figure 13. Proportional-Integral-Derivative (PID) controller.

In the implementation of drone control systems, the theoretical foundations of PID controllers find tangible expression through the utilization of PID blocks in Simulink. This software-based approach seamlessly translates PID theory into practical drone control, enabling engineers and researchers to design, test, and refine control algorithms with remarkable efficiency. By configuring PID blocks in Simulink, specific control parameters such as proportional gains, integral time constants, and derivative time constants can be meticulously tuned to match the dynamics of the drone model. This fine-tuning process ensures that the PID controllers can precisely regulate the drone's altitude, orientation, and position in response to varying inputs and environmental conditions. Moreover, Simulink's intuitive interface facilitates real-time simulations and iterative adjustments, enabling the seamless integration of PID control strategies into the drone model. As a result, the theory of PID controllers comes to life, delivering a robust and adaptive control framework that underpins the successful operation of drones across a spectrum of applications.

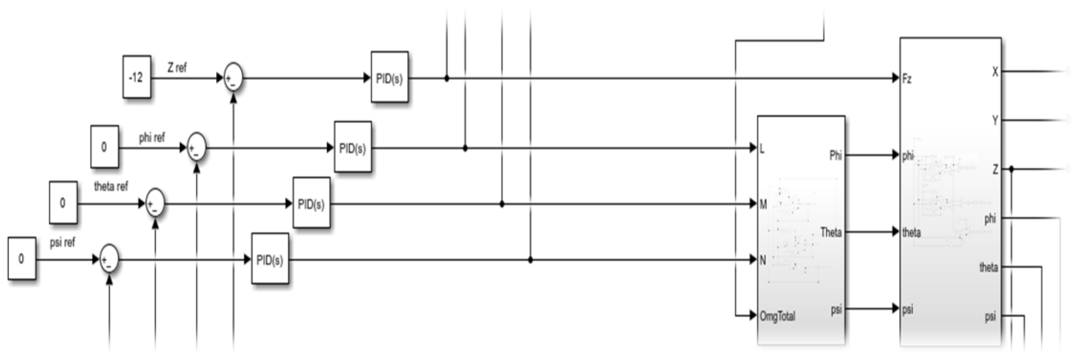


Figure 14. PID controllers application for altitude control.

5.2 Results

With the completion of the drone model, meticulously designed for stable hovering, the stage is set for input application and controller tuning. In this specific scenario, constant input values are poised to be introduced, including zero angular orientations and a meticulously chosen altitude reference.

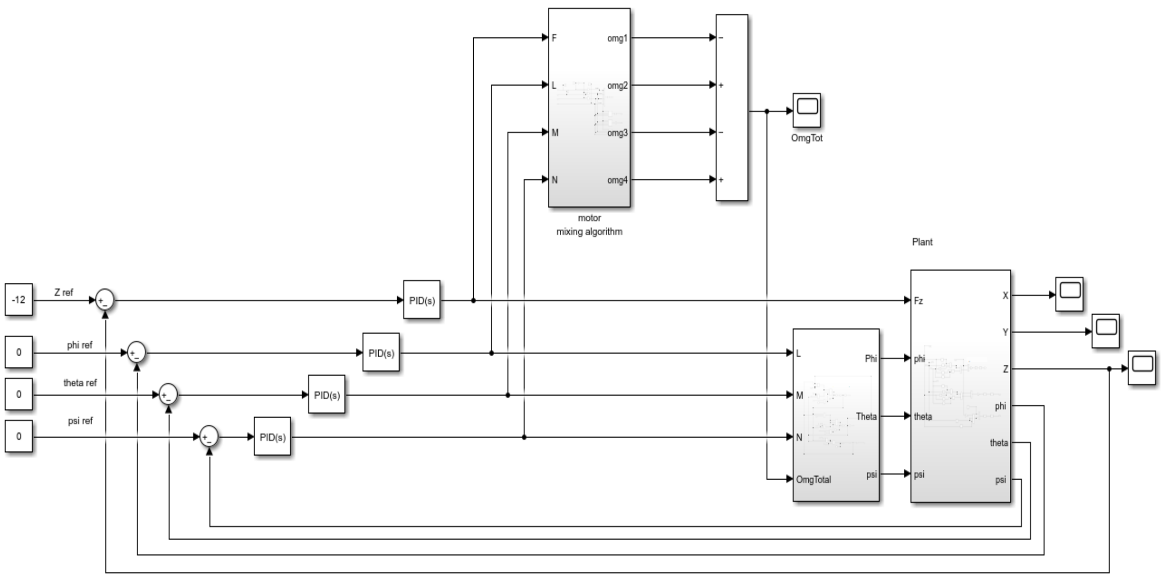


Figure 15. Complete design for altitude control in Simulink

The utilization of a PID controller, fine-tuned with the assistance of the AutoTune tool, has ensured robust and stable altitude control. This tool's capacity to linearize the model contributes to the precision of the tuning process, guaranteeing an optimal response. It is important to note that the other PID controllers responsible for roll, pitch, and yaw can remain at their default settings, as the reference values for these angles are consistently set to zero, ensuring the drone's level orientation during its maneuvers. This strategic approach results in a comprehensive control system that effectively addresses the drone's altitude while preserving other crucial aspects of its flight dynamics. The results can be seen in figure (16):

K_p=146.8
K_i=245.7
K_d=19.5

Table 2. K gains values for the simple hover model.

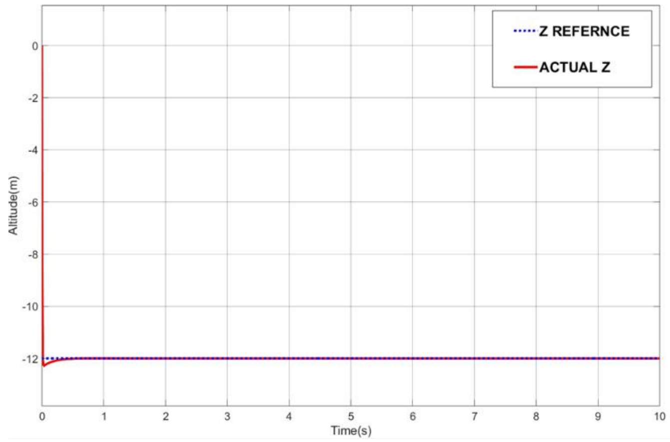


Figure 16. Altitude Control (Simple Hover Model).

Before transitioning to the comprehensive model for position control, a notable consideration emerges concerning the simplified hover model described earlier. It's essential to acknowledge that while this model correctly assumes zero Euler angles, which is suitable for maintaining a stationary drone, it presents limitations. When the drone deviates even slightly from its initial position, say due to factors like wind, it diligently attempts to retain its zero angles and reference altitude. However, this singular focus on maintaining altitude may lead to unintended consequences. In scenarios where the drone's position continually shifts, despite maintaining the desired altitude, the drone can inadvertently drift away from its starting point. This subtle yet critical nuance underscores the need for a more advanced model that not only stabilizes altitude but also accounts for changes in position.

5.3 Position Control / Final design

With the successful development of the altitude control system for the drone, a solid foundation has been established for the subsequent and final stage of this research – position control. Whereas altitude control focuses on maintaining a specific vertical height, the forthcoming phase broadens the scope to spatial positioning. Position control is a critical aspect of this research, encompassing the drone's ability to navigate within a designated environment, accurately reaching and sustaining specific locations. This is particularly essential for applications such as aerial mapping, surveillance, and autonomous navigation. The following sections will delve into the principles and methodologies that underlie the drone's position control design, emphasizing its significance in achieving the overall objectives of this study.

5.3.1 Model design

The position control system is built upon the same core model as previously employed in the altitude control design. This consistency includes the retention of the same system dynamics (plant) and motor mix algorithm block. Furthermore, a close feedback loop is maintained to ensure precise control. However, the primary divergence lies in the inputs to this system. While altitude control predominantly concerned the vertical dimension, the current objective encompasses a more extensive spatial dimension. The inputs now include not only altitude z but also lateral movement along the x and y axes.

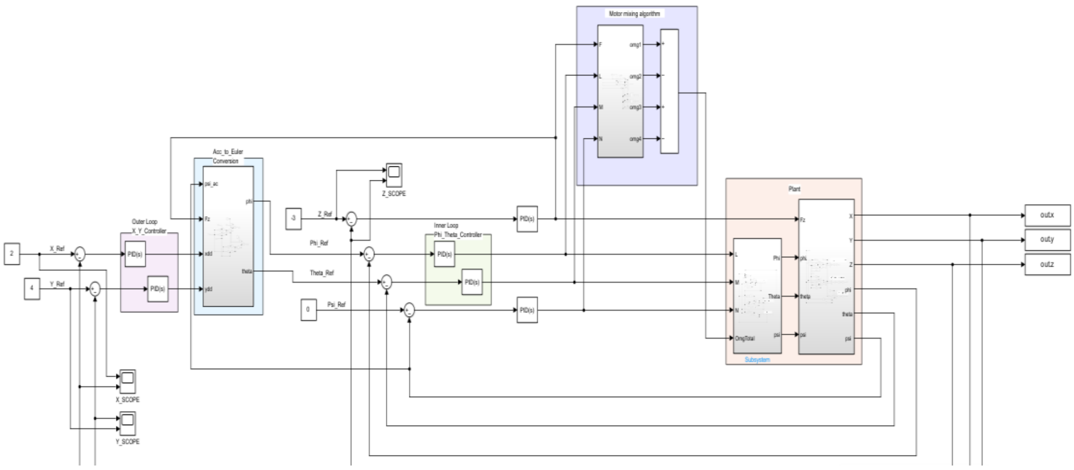


Figure 17. Complete design for position control in Simulink.

In this drone model, we encounter a sophisticated design featuring six Proportional-Integral-Derivative (PID) controllers. Three of these PID controllers are dedicated to orchestrating precise translational motion control, while the remaining three are tasked with fine-tuning rotational movements. This model operates with four inputs, three of which govern spatial coordinates in the x, y, and z axes to fulfill the drone's three-dimensional positioning objectives. The fourth input is allocated to manage the drone's yaw angle, presently set at an arbitrary zero degrees. This control strategy refines the roll and pitch angles to match the desired orientation, initially processing x and y control signals through PID controllers. Subsequently, angular reference points undergo further refinement through a conversion block, translating PID output signals into the corresponding desired angles. Notably, this model employs a dual-loop control structure, encompassing both inner and outer loops. This is commonly referred to as a cascaded control strategy.

The utilization of cascaded control in drone systems, particularly the sequence of employing XY position control followed by Phi-Theta (roll and pitch) control, is a well-thought-out strategy driven by the inherent dynamics and complexities of drone flight.

Cascaded control strategies are implemented to manage complex systems effectively. In the case of drones, the decision to first employ XY position control serves a specific purpose. Drones primarily navigate in the horizontal plane by adjusting their roll and pitch angles (Phi and Theta). These angles, in turn, generate the moments necessary for horizontal motion.

By first stabilizing the XY position, which entails managing horizontal movement and maintaining a set point in space, the cascaded control approach ensures that the drone remains within its intended position. Once XY position control is established, the Phi-Theta control can focus on regulating the orientation angles, ultimately enhancing the drone's horizontal stability.

The primary reason for this sequential approach is that without a stable position control, controlling orientation angles alone can lead to undesirable drift. For example, if the XY position is not adequately managed, the drone could potentially tilt due to external disturbances, even if the orientation angles are correctly controlled. This approach helps address the issue of simultaneous control of position and orientation, aligning the drone's movements with the pilot's or the system's intended commands.

In summary, cascaded control for drones, starting with XY position control and subsequently managing orientation angles like Phi and Theta, ensures a systematic and effective way to navigate the complexities of drone flight, striking a balance between position and orientation control for stable and precise movements.

5.3.2 Conversion Block

F_z, which represents the thrust, is not a suitable control input for influencing the x and y positions of the quadrotor's trajectory. Instead, control over the x and y positions is achieved through adjustments in the roll and pitch angles. This distinction arises from the fundamental nature of quadrotor operation, where it relies on maintaining a hover position. To effectively control these positional coordinates, it is imperative to ensure minimal angle values for the roll and pitch angles. In this context, for simplifying the translation dynamics, small-angle approximations are applied. These approximations involve substituting trigonometric functions, such as sin(phi desired) and sin(theta desired), with their corresponding angle values phi desired and theta desired, respectively. Additionally, for cosine functions, such as $\cos(\phi)$ and $\cos(\theta)$, a value of 1 is used to simplify the mathematical expressions. This strategic simplification aligns with the quadrotor's operational requirements and allows for more straightforward control over its x and y positions, enhancing overall stability during trajectory tracking [4].

So, the equations (3.7) and (3.8) are now become:

$$\ddot{x} = -\frac{1}{m}[F_z(\varphi sin\psi + \theta cos\psi) \tag{5.1}$$

$$\ddot{y} = \frac{1}{m}[F_z(\varphi cos\psi - \theta sin\psi)] \tag{5.2}$$

Where φ and θ represent the desired Euler angles fed into the inner control loop, while ψ denotes the actual yaw angle derived from the system's plant. It is noteworthy that the PID controller's output for controlling the drone's X and Y positions corresponds to the acceleration along the respective axes. Finally, the following equations have been derived:

$$\varphi = \frac{m}{F_z}(sin\psi \cdot \ddot{x} - cos\psi \cdot \ddot{y}) \tag{5.3}$$

$$\theta = \frac{m}{F_z}(cos\psi \cdot \ddot{x} + sin\psi \cdot \ddot{y}) \tag{5.4}$$

Transposing these equations into the Simulink platform:

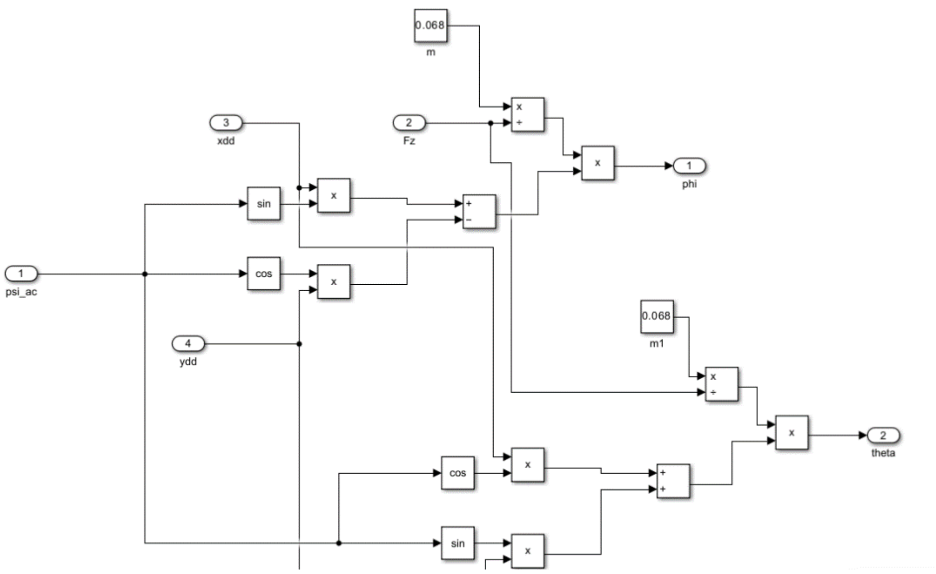


Figure 18. Accelerations in space to Euler angles**.**

5.3.3 Results

In the final phase of this study, the model's outcomes and accompanying graphs vividly illustrate the effectiveness of PID controllers, which were fine-tuned using automated methods [15]. These results highlight the controllers' pivotal role in achieving precise trajectory tracking and position control, with broader implications for robotics and autonomous systems.

<table>
<tr>
<td>

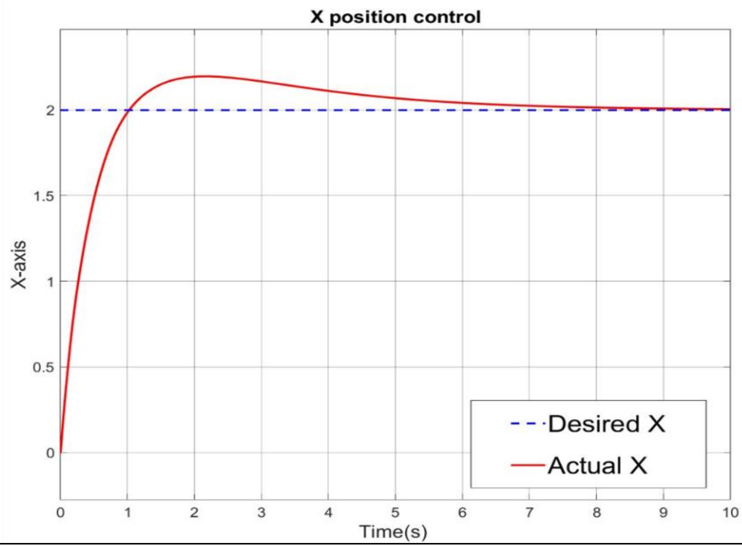
<u>K gains values:</u>

K_p= -16.81

K_i= -6.16

K_d= -10.52

</td>
<td>



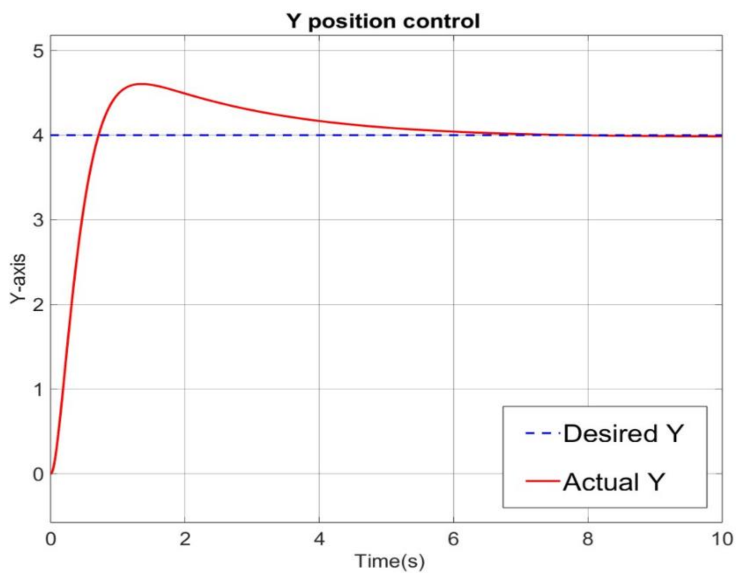
</td>
</tr>
<tr>
<td>

K_p= -1.49

K_i=-0.20

K_d= -2.72

</td>
<td>



</td>
</tr>
</table>

K_p= 16.66

K_i=9.00

K_d=5.43

Table 3. K gains of XYZ position's PIDS.

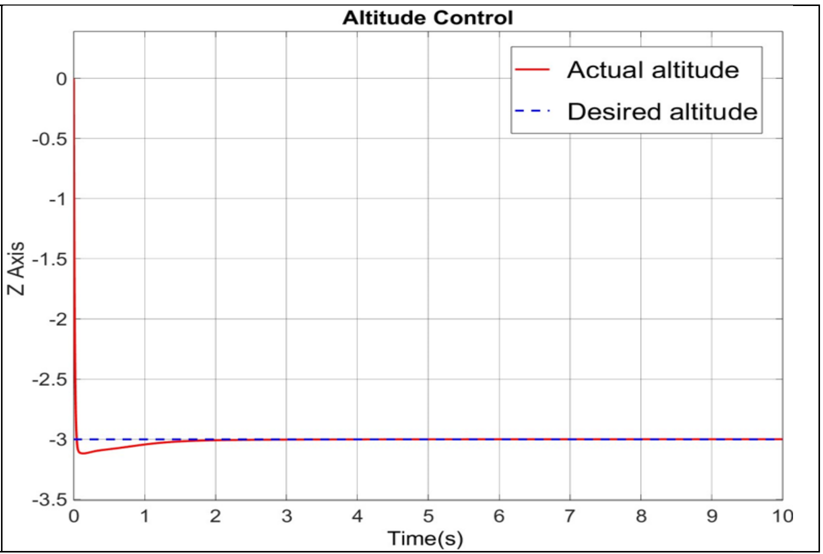


Figure 19. Graphical Representation of position control.

Also, for Euler angles the K gain are the following:

Angles	K_p	Ki	K_i
Φ-phi	*25.22*	*373.06*	*0.39*
Θ-theta	*8.48*	*31.48*	*0.94*
Ψ-psi	*0.15*	*0.47*	*0.007*

Table 4. K gains of the PID controllers for Euler angles.

A three-dimensional plot of the drone's XYZ coordinates it's been presented, offering a visual depiction of the trajectory and position control. The positive altitude readings, despite the drone's downward-facing z-axis, will be thoroughly explored in the forthcoming appendix.

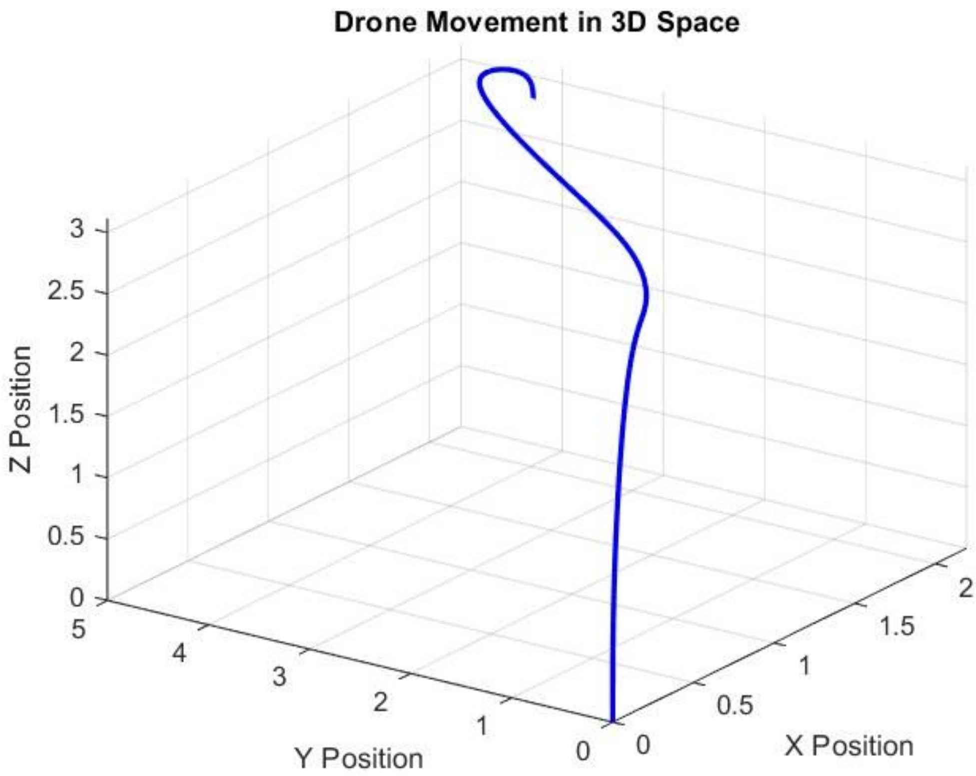


Figure 20. Drone Movement in 3D Space.

6. Conclusion

6.1 Summary and Conclusions

In conclusion, the journey through the realm of quadcopter control design using PID controllers in Simulink has been both illuminating and challenging. The primary objective of this thesis was to develop control systems for quadcopters to regulate their position, commencing with a fundamental hover control model and progressing towards a comprehensive position control system. Throughout this endeavor, Simulink emerged as a powerful tool, allowing us to breathe life into complex equations and facilitating the creation of a functional control model.

This research was not without its hurdles, as the initial stages presented challenges in selecting the appropriate modeling approach, particularly concerning the determination of the number of state variables. Moreover, the simultaneous tuning of all six PID controllers demanded meticulous attention and patience. However, with dedication and perseverance, these obstacles were surmounted, resulting in the successful design of a robust quadcopter control system.

The research conducted in this thesis has not only deepened our understanding of quadcopter control but has also shed light on the remarkable capabilities of Simulink as a versatile platform for implementing complex control strategies. It underscores the significance of rigorous research, practical application, and the tenacity to overcome obstacles in the ever-evolving landscape of engineering and control systems.

Looking ahead, the insights gained through this work have the potential to drive further innovation in the field of quadcopter control, providing valuable contributions to the realm of aerial robotics and beyond. This thesis, with its combination of theoretical rigor and practical implementation, serves as a foundation for future research and development in the quest for precise, efficient, and reliable quadcopter control strategies.

6.2 Future work

In the realm of prospective research, there are several avenues to explore that can further enhance the quadcopter control system. These avenues encompass advancements in the dynamic modeling of the drone, the incorporation of advanced sensor technologies, and the exploration of more sophisticated control strategies.

One area of prospective research involves refining the dynamic model of the quadcopter. While the current model provides a solid foundation, further improvements can be achieved by transitioning from Euler acceleration equations to the utilization of PQR (angular rate) equations. This transition allows for a more accurate and detailed representation of the drone's dynamics, enabling a finer-grained understanding of its behavior and facilitating enhanced control.

The integration of sensors, specifically an Inertial Measurement Unit (IMU) consisting of gyroscope and accelerometer sensors, stands as another promising avenue for future work. The inclusion of an IMU enhances the quadcopter's ability to perceive its orientation and motion with increased precision. This, in turn, enables the control system to make more informed decisions and adjustments, contributing to the overall robustness and stability of the quadcopter.

In parallel with these advancements in modeling and sensor technology, the exploration of more advanced control strategies is a critical next step. Moving beyond the conventional Proportional-Integral-Derivative (PID) controllers, future research can delve into the application of advanced control techniques such as Model Predictive Control (MPC) or Linear Quadratic Regulators (LQR). These strategies offer the potential for greater control precision, adaptability, and responsiveness in varying flight conditions, ultimately leading to improved performance.

The ultimate aspiration of this prospective research is the practical application of these developments to a real quadcopter. The transition from simulation to hardware presents a formidable challenge, encompassing the integration of advanced modeling, sensor technology, and control strategies into a physical drone. Successful implementation in hardware signifies the culmination of this research, demonstrating the feasibility and real-world applicability of the developed control system.

In conclusion, the future work in quadcopter control promises to push the boundaries of knowledge and practice in this field. Advancements in dynamic modeling, sensor integration, and control strategy refinement will collectively contribute to the evolution of quadcopter technology, ultimately paving the way for the deployment of more capable and versatile aerial robotic systems.

Bibliography

[1] Aminurrashid Noordin, Mohd Ariffanan, Mohd Basri & Zaharuddin Mohamed (2022) Position and Attitude Tracking of MAV Quadrotor Using SMC-Based Adaptive PID Controller. Drones. 4-8 https://doi.org/10.3390/drones6090263

[2] A. R. Khairuddin, M. S. Talib and H. Haron (2015) Review on simultaneous localization and mapping (SLAM). In Proceedings of 2015 IEEE International Conference on Control System, Computing and Engineering (ICCSCE). Doi: 10.1109/ICCSCE.2015.7482163.

[3] A. Singandhupe and H. M. La(2019) A Review of SLAM Techniques and Security in Autonomous Driving. In Proceedings of the 2019 Third IEEE International Conference on Robotic Computing (IRC). doi: 10.1109/IRC.2019.00122.

[4] Aws Abdulsalam, Najm & Ibraheem Kasim Ibraheem (2019) Nonlinear PID controller design for a 6-DOF UAV quadrotor system. Submitted in University of Baghdad – College of Engineering, Electrical Engineering Department. Engineering Science and Technology, an International Journal. 1088-1090

https://www.researchgate.net/publication/331601122_Nonlinear_PID_controller_design_for_a_6-DOF_UAV_quadrotor_system

[5] Basic Air Data (2015) *Coordinate System* https://www.basicairdata.eu/knowledge-center/background-topics/coordinate-system/

[6] Haifeng Lyu (2017) Multivariable Control of a Rolling Spider Drone. Submitted in University of Rhode Island. 7-13. https://doi.org/10.23860/thesis-lyu-haifeng-2017

[7] H. Cheng and Y. Yang (2017) Model predictive control and PID for path following of an unmanned quadrotor helicopter. In Proceedings of the 2017 *12th IEEE Conference on Industrial Electronics and Applications (ICIEA)*. Doi: 10.1109/ICIEA.2017.8282943.

[8] Hrishitva Patel (2022) Design and Testing of a Pid Controller on a Parrot Minidrone. *Eduvest - Journal Of Universal Studies. 1948-1950 doi: 10.36418/eduvest.v2i10.606*

[9] Huan Nguyen, Mina Kame, Kostas Alexis & Roland Siegwar (2020) Model Predictive Control for Micro Aerial Vehicles: A Survey. Submitted in arXiv. Doi: 10.48550/arXiv.2011.11104

[10] IMPERIAL WAR MUSEUMS *A Brief History of Drones.* https://www.iwm.org.uk/history/a-brief-history-of-drones

[11] MathWorks (2017) *Programming Drones with Simulink* https://www.mathworks.com/videos/programming-drones-with-simulink-1513024653640.html?s_eid=PSM_15028

[12] MathWorks (2017) Drone Simulation and Control https://www.mathworks.com/videos/series/drone-simulation-and-control.html

[13] MathWorks. PID Controller https://www.mathworks.com/help/simulink/slref/pidcontroller.html

[14] MathWorks. *Quadcopter Project.* https://www.mathworks.com/help/aeroblks/quadcopter-project.html?searchHighlight=mathworks%20quadcopter&s_tid=srchtitle_support_results_1_mathworks%20quadcopter

[15] MathWorks. PID Controller Tuning in Simulink https://www.mathworks.com/help/slcontrol/gs/automated-tuning-of-simulink-pid-controller-block.html

[16] M. Liu, F. Zhang and S. Lang (2021) The Quadrotor Position Control Based on MPC with Adaptation. In Proceedings of the 2021 *40th Chinese Control Conference (CCC)*. Doi: 10.23919/CCC52363.2021.9549626.

[17] Mohamed Okasha, Jordan Kralev & Maidul Islam (2022) Design and Experimental Comparison of PID, LQR and MPC Stabilizing Controllers for Parrot Mambo Mini-Drone. Aerospace. 3-5 https://www.mdpi.com/2226-4310/9/6/298

[18] M. Zaffar, S. Ehsan, R. Stolkin and K. M. Maier (2018) Sensors, SLAM and Long-term Autonomy: A Review. In Proceedings of the 2018 International Conference on RoboticsNASA/ESA Conference on Adaptive Hardware and Systems (AHS). Doi: 10.1109/AHS.2018.8541483.

[19] Nicholas Ferry (2017) Quadcopter Plant Model and Control System Development With MATLAB/Simulink Implementation. Submitted in Kate Gleason College of Engineering. 32-39. http://www.ritravvenlab.com/uploads/1/1/8/4/118484574/ferry.pdf

[20] Trong-Thang Nguyen (2019) The linear quadratic regular algorithm-based control system of the direct current motor. Submitted in Faculty of Energy Engineering, Thuyloi University, Vietnam. *International Journal of Power Electronics and Drive System.* Doi: 10.11591/ijpeds.v10.i2.pp768-776

[21] VDEngineering/Youtube. (2017) *MATLAB & Simulink Tutorial: Quadrotor UAV Trajectory and Control Design (PID + Cascaded).* https://www.youtube.com/watch?v=iS5JFuopQsA

[22] Y. Cai, E. Zhang, Y. Qi and L. Lu (2022)A Review of Research on the Application of Deep Reinforcement Learning in Unmanned Aerial Vehicle Resource Allocation and Trajectory Planning. In Proceedings of the 2022 *4th International Conference on Machine Learning, Big Data and Business Intelligence (MLBDBI)*. Doi: 10.1109/MLBDBI58171.2022.00053.

[16] Y. Cai, E. Zhang, Y. Qi and L. Lu (2022)A Review of Research on the Application of Deep Reinforcement Learning in Unmanned Aerial Vehicle Resource Allocation and Trajectory Planning. In Proceedings of the 2022 *4th International Conference on Machine Learning, Big Data and Business Intelligence (MLBDBI)*. Doi: 10.1109/MLBDBI58171.2022.00053.

Appendix

This appendix “explores” the use of the plot3 function in MATLAB for transforming Simulink-generated data into 3D visualizations. plot3 offers a powerful tool for understanding and analyzing drone trajectories and control system performance, making it a valuable asset in the field of control system design.

The data is initially extracted from Simulink employing the "To Workspace" block, facilitating the seamless transfer of data from Simulink to MATLAB.

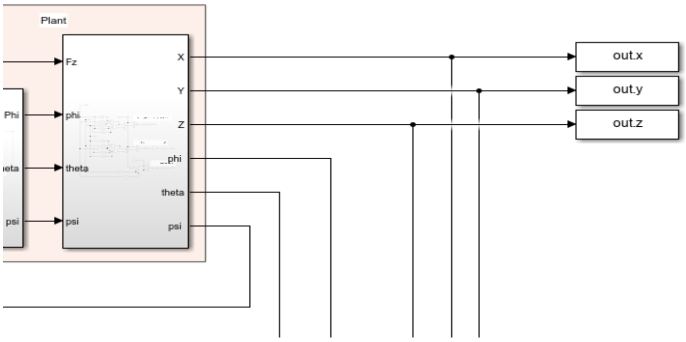


Figure 21. Transferring Data from Simulink to MATLAB

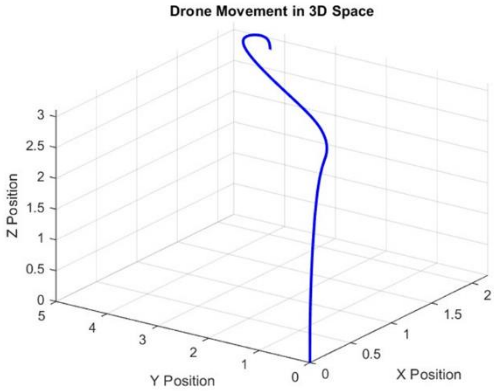
Subsequently, this saved data, is retrieved and visualized in 3D using the following code:

```
% Load the logged data from Simulink
load('sss.mat', 'out');

% Extract relevant data (e.g., x, y, and z positions)
time = out.tout;  % Assuming 'time' is a double array
x_pos_series = out.x;
y_pos_series = out.y;
z_pos_series = out.z;

% Extract numeric values from timeseries data
x_pos = x_pos_series.Data;
y_pos = y_pos_series.Data;
z_pos = - z_pos_series.Data;

% Create a 3D plot of drone movement
figure;
plot3(x_pos, y_pos, z_pos, 'b-', 'LineWidth', 2);
xlabel('X Position');
ylabel('Y Position');
zlabel('Z Position');
title('Drone Movement in 3D Space');
grid on;
```



It is worth noting that the negative Z direction is represented in the plot, causing the Z-axis to exhibit positive values, even though it was initially described as facing downward in the NED (North-East-Down) system.