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CONTROL IN UNMANNED AERIAL VEHICLES

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CONTROL IN UNMANNED AERIAL VEHICLES

By Mouss-ab Moussa DIRIEH

November 2023

We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science

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ABSTRACT

CONTROL IN UNMANNED AERIAL VEHICLES

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November 2023

Quadcopter technology has significantly progressed, yet achieving precise control and stable flight in varying conditions remains a challenge. Current control systems, particularly Proportional-Integral-Derivative (PID) controllers, struggle with the dynamic nature of quadcopter flight, often failing to maintain desired attitudes and positions with precision. The integration of PID controllers with advanced estimation algorithms like the Extended Kalman Filter (EKF) is a potential solution, promising to enhance control by balancing responsiveness and stability against unpredictable factors like wind gusts, system dynamics, and sensor inaccuracies. This study aims to investigate the efficacy of integrating PID controllers with the EKF in quadcopter flight control. The research will explore how these systems' combined strengths might improve precision, adaptability, and autonomy in flight control. The study will focus on implementing a PID controller for error minimization between desired trajectories and actual flight paths, and evaluate the EKF's role in improving state estimation accuracy by fusing data from multiple sensors. The integration aims to create a robust control system, adaptable to environmental changes and capable of complex maneuvers like indoor navigation, obstacle avoidance, and tracking moving targets.

2023, 50 pages

Keywords: Quadcopters, Extended kalman filter, PID control

ÖZET

İNSANSIZ HAVA ARAÇLARININ KONTROLÜ

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Quadcopter teknolojisi önemli ölçüde ilerlemiş olmasına rağmen, değişen koşullarda hassas kontrol ve stabil uçuşu gerçekleştirmek hala bir meydan okumadır. Mevcut kontrol sistemleri, özellikle Orantısal-İntegral-Türev (PID) kontrolörleri, quadcopter uçuşunun dinamik doğasıyla başa çıkmakta zorlanmakta, genellikle istenen tutumları ve pozisyonları hassasiyetle koruyamamaktadır. PID kontrolörlerinin Genişletilmiş Kalman Filtresi (EKF) gibi gelişmiş tahmin algoritmaları ile entegrasyonu, rüzgar darbeleri, sistem dinamikleri ve sensör hataları gibi öngörülemeyen faktörlere karşı duyarlılığı ve stabiliteyi dengeleyerek kontrolü geliştirme potansiyeline sahiptir. Bu çalışma, quadcopter uçuş kontrolünde PID kontrolörlerinin EKF ile entegrasyonunun etkinliğini araştırmayı amaçlamaktadır. Araştırma, bu sistemlerin birleşik güçlerinin uçuş kontrolünde hassasiyeti, uyumluluğu ve otonomiyi nasıl iyileştirebileceğini keşfedecektir. Çalışma, istenen yörüngeler ve gerçek uçuş yolları arasındaki hatayı en aza indirmek için bir PID kontrolörünün uygulanmasına ve EKF'nin, birden fazla sensörden gelen verileri birleştirerek durum tahmini doğruluğunu artırmadaki rolünü değerlendirmeye odaklanacaktır. Entegrasyon, çevresel değişikliklere uyum sağlayabilen ve kapalı alan navigasyonu, engel kaçınma ve hareketli hedefleri takip etme gibi karmaşık manevralar yapabilen sağlam bir kontrol sistemi oluşturmayı amaçlamaktadır.

2023, 50 sayfa

Anahtar Kelimeler: Quadcopters, Genişletilmiş kalman filtresi, PID kontrolü

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Mouss-ab Moussa DIRIEH
Çankırı-2023

CONTENTS

LIST OF ABBREVIATIONS

BLDC	Brushless direct current
CW	Clockwise
CCW	Counterclockwise
ESC	Electronic speed controller
EKF	Extended kalman filter
PID	Proportional integral derivative
PWM	Pulse width modulation

LIST OF FIGURES

1. INTRODUCTION

The story of drones, or unmanned aerial vehicles (UAVs), unfolds like a fascinating chapter in the annals of technological progress. Originating in the early 20th century, the evolution of drone technology spans from rudimentary aerial targets and wartime instruments to sophisticated tools reshaping both military strategy and civilian life. This narrative is not just about machines; it is about human ingenuity, the relentless pursuit of advancement, and the unforeseen consequences of innovation. In the throes of World War I, the concept of an unmanned aircraft transitioned from theory to reality. Countries like the United Kingdom and the United States pioneered the development of these early drones, utilizing them for target practice and, more ambitiously, as airborne carriers of explosives. Two landmark British projects, the Larynx and the Ram, epitomize the aspirations and hurdles of this era, marking the first significant steps in drone technology under the shadow of evolving warfare tactics and an expanding aerial battleground (Priya 2014). As we traverse through the decades, we witness the transformation of drones from mechanical novelties to pivotal components in modern warfare, surveillance, and a myriad of civilian applications. From the inter-war period's experimental ventures to the Cold War's strategic reconnaissance missions, and into the 21st century's surge in both military and commercial drone usage, each phase presents a unique intersection of technological breakthroughs, strategic shifts, and ethical quandaries. This account not only explores the historical milestones and technological advancements of drones but also delves into their expanding role in fields like agriculture, scientific research, and emergency response. As we navigate through the dynamic landscape of drone technology, we also confront the intricate tapestry of challenges it presents – from privacy concerns and ethical implications to the futuristic possibilities that continue to unfold (Kendra 2007, Katharine 2016).

Unmanned aircraft have a rich and extensive history that predates the common understanding of many individuals. Although the term "drone" has become popular recently, the exploration of unmanned flight has a significant history. According to the Merriam-Webster dictionary, drones are unmanned aircraft that are operated remotely or by onboard computers. The concept, as illustrated in Figure 1.1, was inspired by kites.

Figure 1.1 Kites

Around 1000 BCE, these were created in China, with the earliest ones primarily used for religious and cultural celebrations. During the Song Dynasty (960–1279), kites served for signaling, reconnaissance, and even for lifting warriors into the air. Meanwhile, in France, balloons emerged in the 18th century. The Montgolfier brothers launched the first manned hot air balloon in 1783, opening new possibilities for aerial travel and exploration. Drone technology may trace its origins to Austria's 1849 attack on Venice, which involved unmanned balloons loaded with explosives. According to Interesting Engineering, around 200 of these incendiary balloons were released over Venice by Austrian forces besieging the city. Each balloon carried between 24 pounds (11 kg) and 30 pounds (14 kg) of bombs. These explosives were to be dropped from their carrier balloons to devastate the city below. Fortunately for the Venetians, only one bomb reached its target due to a sudden change in wind direction that caused most of the balloons to go off course.

1.1 Problem Statement

Quadcopter technology has advanced significantly, yet challenges persist in achieving high-precision control and stable flight under varying conditions. Current control systems, while capable, often fall short in handling the dynamic nature of quadcopter flight, particularly when dealing with environmental disturbances and complex autonomous navigation requirements. Proportional-Integral-Derivative (PID) controllers, despite their widespread use for flight stabilization and control, sometimes fail to maintain the desired attitude and position with the necessary precision. The integration of PID controllers with sophisticated estimation algorithms like the Extended Kalman Filter (EKF) has the potential to enhance flight control but has not been extensively explored. This integration may offer a solution to the persistent problem of achieving a balance between responsiveness and stability in the face of unpredictable variables such as wind gusts, system dynamics, and sensor inaccuracies. There is a need for a control system that can not only manage the intrinsic instabilities of quadcopter flight but also adapt to unexpected environmental changes. Additionally, for quadcopters to be fully autonomous, they must be capable of sophisticated maneuvers such as indoor navigation, obstacle avoidance, and the tracking of moving targets without compromising on stability or control accuracy. However, the existing control methodologies have limitations in terms of adaptability and robustness, which hampers the quadcopter's performance in real-world applications.

This study seeks to address these challenges by investigating the efficacy of a control system that integrates PID controllers with the EKF. The research aims to understand how the combined strengths of these systems can be harnessed to improve the quadcopter's flight control in terms of precision, adaptability, and autonomy. The study will evaluate the performance of this integrated control system through a series of metrics, including control accuracy, response time, and stability, and will consider its practical applications in various industries. By exploring this integration, the research aims to contribute to the development of more reliable and versatile quadcopter technologies for commercial, surveillance, and search and rescue operations.

1.2 Objective and Scopes

The primary aim of this research is to investigate the efficacy of integrating Proportional-Integral-Derivative (PID) controllers with the Extended Kalman Filter (EKF) in the regulation and stabilization of quadcopter flight. The study seeks to understand how the synergistic application of these two control systems can enhance the quadcopter's ability to maintain its attitude and position with precision, particularly under varying operational conditions. A further objective is to evaluate the improvement in autonomous navigation capabilities that this integration provides, enabling the quadcopter to handle complex maneuvers and adjust to environmental disturbances more effectively. The study focuses on the implementation of a PID controller in a quadcopter to minimize error between desired trajectories and actual flight paths. It evaluates the Extended Kalman Filter's contribution to state estimation accuracy by fusing data from multiple sensors and refining the quadcopter's model. The study also explores the integration of PID controllers and Extended Kalman Filter in a single control framework to create a more robust control system. It investigates the system's adaptability to environmental changes and disturbances, ensuring reliable operation under various conditions. The study also examines the system's autonomous navigation and maneuvering capabilities, including indoor and outdoor navigation, obstacle avoidance, and dynamic tracking of moving objects. Performance metrics are established to quantify improvements in control accuracy, response time, and stability. The study also considers practical applications in fields like surveillance, search and rescue operations, and delivery services, assessing its scalability for commercial use.

1.3 Thesis Organization

The thesis is structured into six chapters, each with a specific focus. The introduction introduces the research topic, stating the research problem, and outlining the main objectives. It discusses the significance of the research and its potential contributions to the field of quadcopter control systems. The literature review is presented in Chapter two, which examines previous studies, current trends, and gaps in the literature. Chapter three provides background information on quadcopters, covering different types, configurations, and movements. It also delves into the aerodynamics and physical principles governing quadcopter flight. Chapter 4 details the materials and methods used in the research, including experimental design, setup of PID controllers and Extended Kalman Filters, and testing procedures. The methodology is explained and its rationale is explained. Chapter five presents the data collected from the experiments and analyzes the results. It discusses the performance of the integrated PID controller and Extended Kalman Filter in various scenarios and interpreting the findings. Finally, chapter six concludes the thesis by summarizing the findings, discussing the implications of the research, and providing recommendations for future work.

2. LITERATURE REVIEW

Leonardo (2013) revolves around the utilization of the extended Kalman filter (EKF) in managing the attitude control system of a quadrotor—a specific type of unmanned aerial vehicle (UAV) equipped with four rotors. The Kalman filter, a mathematical instrument designed for estimating the state of a dynamic system impacted by random noise using noisy measurements, forms the foundation of this research. Despite the Kalman filter's assumption of linearity and normal distribution of noise, the extended Kalman filter, a nonlinear adaptation, has gained widespread acceptance in diverse applications.

Williams-Paul *et al.* (2021) was reported the necessity of their study because the global navigation satellite system (GNSS) units used in current multi-dimensional recreational drones (UAVs) are frequently prone to precise-point-positioning (PPP) data mistakes or inaccuracies. The system's shortcomings, such abrupt GPS lock or jamming, misaligned embedded devices, the drone's patchy communication coverage, signaling, and detection, all lead to these data inadequacies, which increase the PPP calculation complexity of the system. This paper validates an intelligent and reliable accurate hybrid cubature-extended Kalman Filter (C-EKF) calculation model for an integrated GNSS unit that uses continuous-discrete (ACD) data to reduce PPP complexity. More specifically, the third-degree spherical-radial cubature rule is used to update the state and parameter sub-vectors for the GNSS unit over time.

Simone *et al.* (2018) the magnetic and inertial measurement unit (MIMU) supplies real-time data on acceleration, angular velocity, and the Earth's magnetic field. However, this data, on its own, is susceptible to considerable noise, bias, and drift (without regular recalibration). To mitigate these errors, a data fusion algorithm can be employed. Historically, various methods have been employed to filter gyroscope data alongside inertial measurements, with Extended Kalman filtering and complementary filters being the most widely used techniques. This paper compares three methods: two complementary filters, namely Madgwick and Mahony, and the Extended Kalman Filter (EKF). Simulation experiments conducted with quadcopter data reveal that, with optimal parameters, Mahony outperforms both Madgwick and EKF in terms of orientation estimation.

Wenjing (2017) focuses on determining the attitude of a quadcopter using a 3-axes accelerometer, a 3-axes gyroscope, and a 2-axes compass. It introduces fundamental quadcopter concepts, such as roll, pitch, and yaw, along with the coordinate system used for calculations. The mathematical model is established, and the quadcopter is simulated in Simulink with sensors modeled using real measurements to estimate measurement noise accurately. The model undergoes testing with a step input, and the output, along with added Gaussian noise, serves as input for the Extended Kalman Filter (EKF). Comparisons with various Kalman Filters suggest that the EKF is the most effective strategy. The standard Extended Kalman filter is identified as the optimal estimator with correctly set parameters, offering superior results. However, it is noted that, as it is not implemented on the embedded system, the EKF can only be used as a reference, providing satisfactory results in most scenarios.

Sumardi *et al.* (2017) proposed a self-tuning control system employing the Particle Swarm Optimization (PSO) method for bearing navigation. The Global Positioning System (GPS) is utilized to determine the coordinates based on the bearing angle to the destination. The HMC5883L compass sensor calculates the quadcopter's actual angle relative to the Earth's electromagnetic field. According to test results, the quadcopter effectively maintains fixed coordinates with a settling time of 6.4 seconds and an average error after settling time of 5.4°. In coordinate change tests, the quadcopter achieves the target of fixed coordinates with an average error of 7.9°. During disturbance experiments, an average offset error of 1.89° and a settling time of 4.1 seconds are accomplished. The optimal PSO self-tuning parameters are determined as Kp = 0.15 to 0.3, Ki = 0.06 to 0.6, and Kd = 0.005 to 0.1. The PSO values employed include C1 = 1.5, C2 = 2, and an inertia weight ranging from 0.7 to 1.2, based on experimentation.

The genetic algorithm (GA) has been used to improve the coefficients of the proportional-integral-derivative (PID) controller, which regulates the vertical movement of four-motor UAVs. The language used to code GA is Matlab/Script. In the Matlab environment, a mathematical model of a quadrotor was created. The simulation's findings demonstrate that the GA was successful in optimizing the PID controller's coefficients (Zafer 2020).

Salam (2020) propose an innovative algorithm for real-time tuning of Proportional, Integral, and Derivative (PID) controllers for quadcopters is presented. The Particle Swarm Optimization (PSO) method is employed to explore the quadcopter's solution space and find optimal parameters for the PID controller. A Fuzzy Logic (FL) controller generates appropriate velocity reference signals, acting as tracking set points for the PID controller in a cascaded controller configuration. This nested loop design is proposed for stabilizing the quadcopter, with the Fuzzy Logic Controller (FL) operating in the stable loop (master loop) to control the desired angle, and the PID controller in the rate loop (slave loop). The real-time estimated optimal PID parameters are successfully tested on a quadcopter experimental setup, facilitated by the PSO algorithm.

Mojtaba and David (2022) introduce a sliding mode fuzzy control strategy designed for industrial robots operating at static and near-static speeds (linear velocities below 5 cm/s). The extended Kalman filter, incorporating covariance resetting, is utilized to convert Cartesian coordinates to joint angle space. The resulting joint angles serve as a reference signal for controlling the dynamics of the industrial robot through a sliding mode fuzzy controller. The controller's stability and robustness are established using a Lyapunov function, considering parameter uncertainty and unknown dynamic friction. Simulations are conducted on a 6-DOF industrial robot, specifically the Universal Robot-UR5, accounting for maximum allowable joint torques. The proposed controller effectively manages UR5 amid uncertainties, including unknown dynamic friction and parameter variations. Comparative analysis with a sliding mode control approach demonstrates superior tracking performance of the proposed method in the presence of uncertainties.

Pengcheng *et al.* (2016) proposed a cascade PID feedback control algorithm aimed at stabilizing the attitude of a quadcopter, ensuring a balanced state in the presence of disturbances. The quadcopter's dynamics are modeled using the Newton-Euler method, yielding precise relationships among all variables. Subsequently, both linear and nonlinear state-space equations are derived, providing crucial foundations for controller design and further exploration. Simulations are conducted to illustrate the efficacy and robustness of the cascade PID algorithm in comparison to the traditional PID control scheme.

Feng *et al.* (2017) propose the Qball-X4 quad-rotor unmanned aerial vehicle (UAV), created by Quanser Company, and served as the experimental platform for this investigation. First, they developed a mathematical model that served as the basis for the Qball-X4 quad-rotor UAV, and then they used this model to build a simulation model. The model structure was then followed in the construction of a double closed-loop optimum proportional–integral–derivative (PID) controller using integral of time multiplied by absolute error (ITAE) indices. We created a matching Kalman filter that can estimate the goal trajectory in order to mitigate any system defects and data delays. To guarantee its efficacy, the suggested PID controller was positioned ahead of this Kalman filter. The system's simulation results, which included the Kalman filter and PID controller that were provided, were then shown to confirm their effectiveness.

Javier *et al.* (2020) presents a control technique for a quadrotor's posture. The proposed technique is based on a Multilayer Perceptron trained with an Extended Kalman Filter and exhibits the behavior of a PD controller. To provide adaptability to changes in the presence of uncertainties and dynamics, the Neural Network is trained online. To demonstrate the efficacy of the control strategy, real-time tests are conducted.

Kodgirwar *et al.* (2014) discusses the design of a Quadcopter control system, focusing on its software implementation. The Quadcopter's control system comprises two main components: a Complimentary filter and a PID block. The Complimentary filter serves as a feedback block, providing the angles along the x and y axes of the Quadcopter. The paper emphasizes the necessity of the Complimentary filter over using just accelerometer and gyroscope directly for angle determination along the x and y axes, as illustrated through graph plots. The PID Controller block calculates the error in angles along the x and y axes, generating an output signal that minimizes the error. The paper highlights the significance of the three constant parameters in the PID Controller. All presented results are validated on an actual Quadcopter and graphically depicted using Matlab and processing software.

Aziz *et al.* (2017) establish a fundamental test bench for our quadcopter, followed by collecting observational data that includes motor parameters and predefined attitude angles. Utilizing the measurement phase, we deduced the differential equations governing our quadcopter. Subsequently, a continuous-time steady-state model was derived from these equations. In Matlab, a linearization process was conducted, subject to constraints such as maximum allowable angle rates in hover position. Then, a PD type classical controller was developed for both altitude and attitude control of the quadcopter. To simulate real-world conditions, Gaussian-distributed noise was introduced as a disturbance to the controlled states of the quadcopter. Finally, a Kalman filter was designed and implemented to estimate the states of the noisy signals, ensuring a reliable control system for the quadcopter.

Jackson *et al.* (2019) employed an Extended Kalman Filter Fuzzy Proportional, Integration, and Derivative (PID) controller to manage a quadcopter in the presence of a 100% fault on a single rotor. The system operates without a fault diagnosis and detection system, relying solely on a single controller. A fuzzy system tunes the PID controller gains, and the optimization of fuzzy Membership Functions (MF) is executed using an Extended Kalman Filter (EKF). The optimized Fuzzy PID controller maintains the system at its set point, restoring it to a stable hovering position. This is achieved by simultaneously adjusting the velocity of the three fault-free rotors. Real-time computation of adaptive PID gains compensates for the effects of rotor failure. The controller stabilizes the attitude and altitude of the quadcopter, facilitating a secure landing without further damage to the quadcopter structure.

3. GENERAL INFORMATION

3.1 Different Types of Drones

Drones, can be configured in a variety of ways depending on how many rotors they have. The drone's flying qualities, stability, cargo capacity, and maneuverability are influenced by the rotor arrangement.

3.1.1 Single rotor helicopter

Monocopters, also known as single-rotor UAVs or single-rotor helicopters, as shown in Figure 3.1, are unmanned aerial vehicles that utilize a single rotor for lift and control. In contrast to quadrotors or multirotors, which employ multiple rotors for stability, monocopters rely on a single main rotor and, occasionally, a smaller tail rotor or control surface to achieve stability and maneuverability. Typically, monocopters feature a main rotor that provides lift and generates the majority of the thrust required for flight. Depending on the design of the monocopter, the main rotor can be positioned either horizontally or vertically. This rotor spins at high speeds, creating the necessary lift that enables the vehicle to hover, ascend, descend, and maneuver effectively (Dhanya *et al.* 2023).

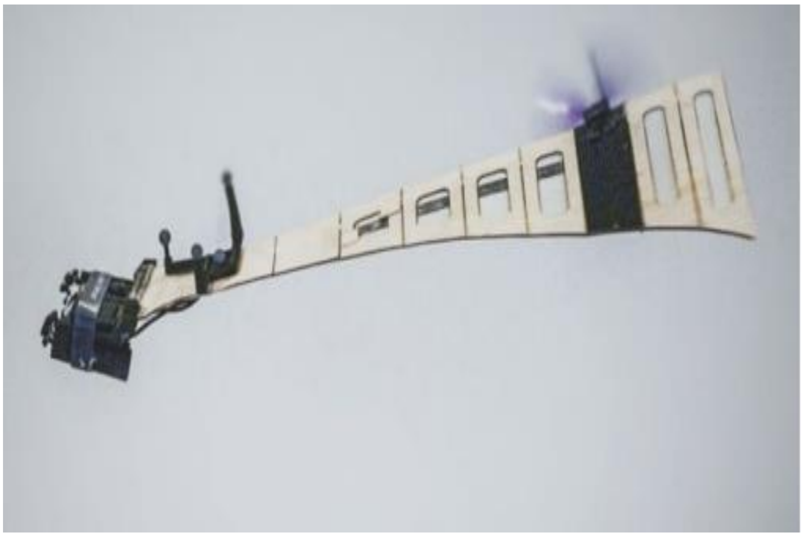

Figure 3.1 Foldable single actuator monocopter (Dhanya *et al.* 2023)

To counteract the torque produced by the main rotor's spin, monocopters may incorporate a smaller tail rotor or utilize control surfaces. These components generate a counteracting force to stabilize the monocopter, preventing it from spinning uncontrollably. In some designs, variable pitch mechanisms adjust the angle of the main rotor blades, eliminating the need for a tail rotor. Achieving stability and control in monocopters can be challenging due to the absence of multiple rotors. The design and control algorithms must compensate for the inherent instability caused by having only one rotor. Sensors such as accelerometers, gyroscopes, and barometers are employed alongside sophisticated flight control systems to stabilize and control the monocopter's flight.

Monocopters have unique flight characteristics compared to multirotors. They are generally more agile and maneuverable, owing to their ability to dynamically change rotor speeds and angles. However, monocopters tend to be less stable when hovering and require constant control adjustments to maintain equilibrium. They are commonly used in scenarios where agility and precise maneuvering are paramount, such as aerobatic displays or research experiments. The payload capacity of monocopters varies based on their size, rotor design, and power. Smaller models may have limited payload capacity, while larger ones can carry more substantial loads, including cameras for aerial photography or sensors for scientific data collection (Shengxiang *et al.* 2022).

Monocopters are less energy-efficient compared to multirotors due to their reliance on a single rotor, which creates significant rotor-induced drag and requires more power to maintain flight. This factor impacts their flight time and endurance. Nonetheless, monocopters are still utilized in specific applications that benefit from their unique flight characteristics, such as in research, experimental platforms, or specialized aerobatic performances (Jun *et al.* 2019).

3.1.2 Tricopter

The mechanical design of the tri-rotor vehicle, as illustrated in Figure 3.2, incorporates a central body with a central axis labeled x-x, uniform radial arms, and a payload that includes a landing kit, controller, and power source. The controller and power source are connected to each rotor for electrical communication. The vehicle comprises two front rotors and one rear rotor, each mounted on one of the three arms. The fixed blade propellers are aligned on a shared plane, and the avionics system modulates the rotational speed of these propellers to control the vehicle's attitude and maneuverability. This design obviates the need for coaxial rotors or an additional servo motor.

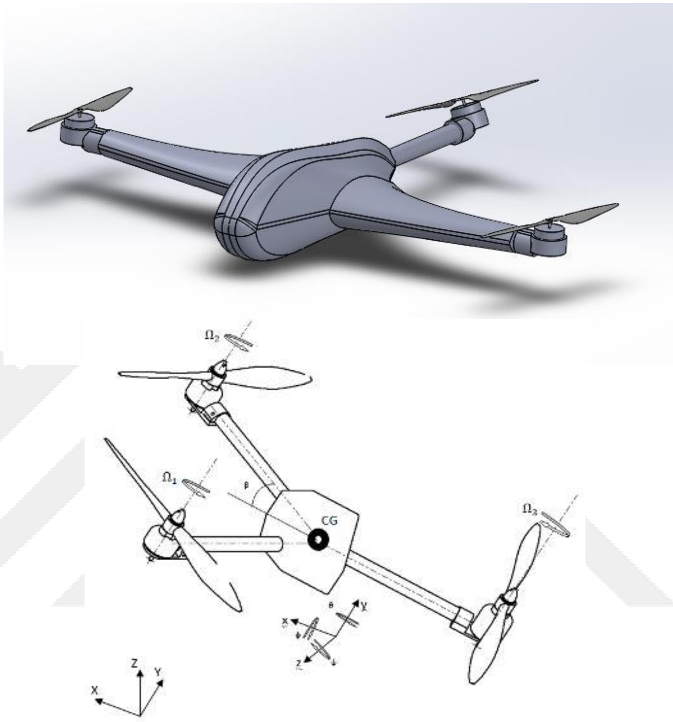

Figure 3.2 Example of tricopter (Hamzeh and Osamah 2015)

An onboard microcontroller regulates the angular speed and torque of the rotors. The two front rotors rotate in the same direction, while the rear rotor spins in the opposite direction, effectively minimizing adverse torque and gyroscopic moment forces. The roll and pitch movements of the vehicle are controlled by varying the rotational speed of the two front rotors. All three motors are brushless DC motors, engineered to produce equal torque and lift. However, to achieve the necessary torque, the rear rotor's mechanical specifications, including propeller dimensions, motor size, and power requirements, must surpass those of the front two rotors (Hamzeh and Osamah 2015, Stephen 2014). Tricopters offer excellent maneuverability due to the independent control of the motors. The differential thrust generated by changing the speed of each motor allows the tricopter to perform complex maneuvers, such as flips, rolls, and sharp turns. They can be equipped with various payloads, such as cameras, sensors, or cargo carriers. They are often used in aerial photography and videography, surveillance, research, or recreational purposes. Tricopters are typically powered by rechargeable lithium polymer (LiPo) batteries. The battery capacity and voltage determine the flight time and power available for the motors (Zarrar *et al.* 2019).

3.1.3 Hexacopter

A hexacopter, as depicted in Figure 3.3, is a type of drone or remote-controlled aircraft characterized by its six rotors, which provide propulsion and maneuverability. This configuration is an extension of the tricopter or quadcopter design, featuring an additional pair of rotors, bringing the total to six. The rotor arrangement in hexacopters offers enhanced stability, increased lifting capacity, and added redundancy. Typically, hexacopters are constructed with a robust frame made from materials such as carbon fiber, aluminum, or plastic. The frame's design accommodates the six rotors, evenly distributing three rotors on each side of the aircraft. This distributed rotor placement affords greater stability and improved lifting capabilities compared to quadcopters or tricopters (Arief *et al.* 2021).

Figure 3.3 Assembling of hexacopter frame and components (Manjarrez *et al.* 2023)

Hexacopters utilize flight controllers similar to other multirotor aircraft. These controllers receive input from either a pilot or an autopilot system, and they adjust the motor speeds accordingly. The flight controller is instrumental in maintaining stability, controlling the hexacopter's attitude, and enabling various flight modes. Due to their increased number of rotors, hexacopters offer exceptional maneuverability and stability. The six rotors enable enhanced control, smoother flight, and the capability to withstand the loss of one or two rotors without losing complete control of the aircraft (Juan *et al.* 2016). Hexacopters are capable of carrying diverse payloads, such as high-resolution cameras, sensors, surveying equipment, or even delivery packages. Their common applications include aerial photography and videography, cinematography, industrial inspections, search and rescue operations, agricultural surveys, and other professional uses. The versatility and enhanced capabilities of hexacopters make them ideal for these tasks (Bhakti *et al.* 2018; Bahareh *et al.* 2019).

One key advantage of hexacopters over quadcopters or tricopters is the redundancy afforded by their additional set of rotors. In case of a rotor failure, a hexacopter can still maintain stable flight and safely land, thanks to the remaining operational rotors. This feature significantly enhances the safety and reliability of hexacopters in various operations (Mina *et al.* 2018). Hexacopters are renowned for their versatility, stability, and lifting capacity. They are well-suited for a wide range of applications that require aerial capabilities beyond what quadcopters or tricopters can offer, making them a preferred choice in many specialized fields (Susitra *et al.* 2020).

3.1.4 Octocopter

An octocopter, as shown in Figure 3.4, is a type of drone or remote-controlled aircraft featuring eight rotors for propulsion and maneuverability. This advanced configuration offers increased stability, lifting capacity, and redundancy compared to hexacopters and quadcopters.

Figure 3.4 Octocopter (Heavy 2023)

He *et al.* (2020) conducted research on three different configurations of octocopters: conventional, coaxial, and a new configuration. Designing helicopter rotor blades is a complex task involving aerodynamics, acoustics, and dynamics. The authors selected the NACA2411 airfoil profile for plastic propellers through extensive simulation calculations, ensuring comparable thrust to realistic rotors of the same radius. The rotor blades were connected to a rotor-conforming hub, resulting in a grid system with two blades per hub. The octocopter had an unloaded weight of 8.85 kg and a fully loaded weight of 20 kg. The fuselage parameters were derived from similar-performing drones. The rotor blades had a radius of 230 mm, and the distance from the vehicle's center to each rotor's rotational axis was 653 mm. The new configuration featured a 234 mm distance between two-layer rotors, while the coaxial configuration had a distance of 32 mm. The chord length was normalized based on the rotor radius, and the blade tip chord length was approximately 30 mm. The study also explored larger rotor blade configurations, which increased thrust in the new and coaxial configurations compared to the conventional configuration, maintaining the same airfoil profile but scaling the rotor parameters proportionally, with the distance to the rotational axis constant at 653 mm. To develop a flight controller, (Riska *et al.* 2016) chose a PID plus Fuzzy controller. PID controllers are frequently used in various applications due to their simplicity, reliability, and capability to produce rapid response times. However, they can result in high overshoot. To address this issue and fully satisfy the need for attitude control, we recommend using a combination of PID and fuzzy controllers. Fuzzy controllers, while having slower response times, are stable and exhibit less overshoot. Thus, by combining these two controllers, we achieve the benefits of both in a Fuzzy+PID controller.

Octocopters have a high payload capacity, making them suitable for carrying heavy payloads in professional applications such as cinematography, aerial photography and videography, industrial inspections, mapping and surveying, search and rescue missions, and delivery operations. They are preferred for tasks that require larger cameras, LiDAR systems, or other specialized equipment (Anthony *et al.* 2019). The superior stability of an octocopter is a significant advantage for capturing clear images, avoiding blurry photographs. Its ability to lift heavy weights due to the strength of its motors is another benefit. Compared to other designs, its primary drawbacks are its size and weight, which negatively impact flight range and increase costs. Coleman (Cp *et al.* 2018) proposed using a coaxial arrangement to address this issue. This configuration, achieved by attaching two oppositely rotating rotors on each arm of the drone, is expected to offer improved stability, longer flight range, and the ability to carry a larger payload (Belmonte *et al.* 2018). Octocopters are considered powerful and versatile aerial platforms due to their stability, lifting capacity, and redundancy. They are commonly used in professional applications where heavy payloads or specialized equipment are required (Meng *et al.* 2013).

3.1.5 Quadcopter

In terms of stability, cost, a variety of structural sizes, ease of construction, and modeling, quadrotors, as depicted in Figure 3.5, undoubtedly offer significant advantages. For these reasons, our focus will be primarily on quadcopters, their structure, take-off strategy, and control algorithms.

Figure 3.5 Quadcopter with camera

A traditional PID controller is commonly used to maintain the quadcopter's balance or to achieve the desired attitude. However, it falls short in delivering reliable performance, whether the control objective is the Euler angle or angular rate. This limitation stems from the fact that the control outputs of a traditional PID controller generally depend only on the error value of the Euler angles, neglecting the impact of angular rate on the system's transient response. To address this, a novel approach known as the cascade PID algorithm has been developed. A cascade control system, which can perform better than the traditional PID controller, especially when multiple sensors are available, comprises two PI controllers connected in series. The output of the primary controller serves as the setpoint for the secondary controller, and the output of the secondary controller feeds back into and influences the primary controller. In the case of a quadcopter, the primary controller is an angle controller that generates the appropriate angular rate as its control output, acting as the setpoint for the secondary controller, which is the angular rate controller. The actual angular rate loop operates significantly faster than the angle loop, allowing adequate time to account for disturbances. In addition to driving the current Euler angle to converge to the target angle, the cascade control also limits the angular rate during convergence. Since both the Euler angle and the angular rate can be detected and regulated in the closed-loop system, the transient response of the cascade controller is substantially smoother than that of a traditional PID controller. This results in a significant enhancement of the quadcopter system's resilience (Pengcheng *et al.* 2016).

3.2 Quadcopter Configurations and Movements

3.2.1 Configuration

Quadcopters utilize four separately controlled actuators to provide relative thrust. To achieve lift, two of its motors must rotate in opposing directions; otherwise, the net moment around the center of mass would not be zero, leading to undesirable movements. In helicopters, this net moment near the center is offset by a tail rotor or tail aerofoil. In quadcopters, however, it is achieved by having any two pairs of rotors rotate clockwise (CW) while the adjacent pairs spin counterclockwise (CCW). Consequently, it has become standard practice for the opposing motors of a quadrotor with a crossing configuration to rotate in opposite directions. There are two main configurations for the placement of the four rotors on a quadcopter: the "+" configuration and the "X" configuration.

In the "+" configuration, as depicted in Figure 3.6, the quadcopter's four rotors are positioned to form a plus sign. The front and back rotors align along one axis, while the left and right rotors align along another axis, perpendicular to the first. This layout offers a symmetrical and balanced structure. The advantages of the "+" configuration include, first, inherent stability due to its symmetrical design. The evenly distributed rotors provide balanced lift and thrust, enhancing the quadcopter's stability in various flight conditions. Second, each rotor corresponds to a specific axis of control: the front and back rotors manage pitch (tilting forward and backward), while the left and right rotors control roll (tilting left and right). The throttle governs the overall lift, and yaw (rotation) is achieved by varying the speeds of the rotors on opposite sides. Lastly, the "+" configuration is relatively simple to construct and maintain. Its frame structure can be straightforward, and the control system can be designed with minimal complexity (Moad *et al.* 2021).

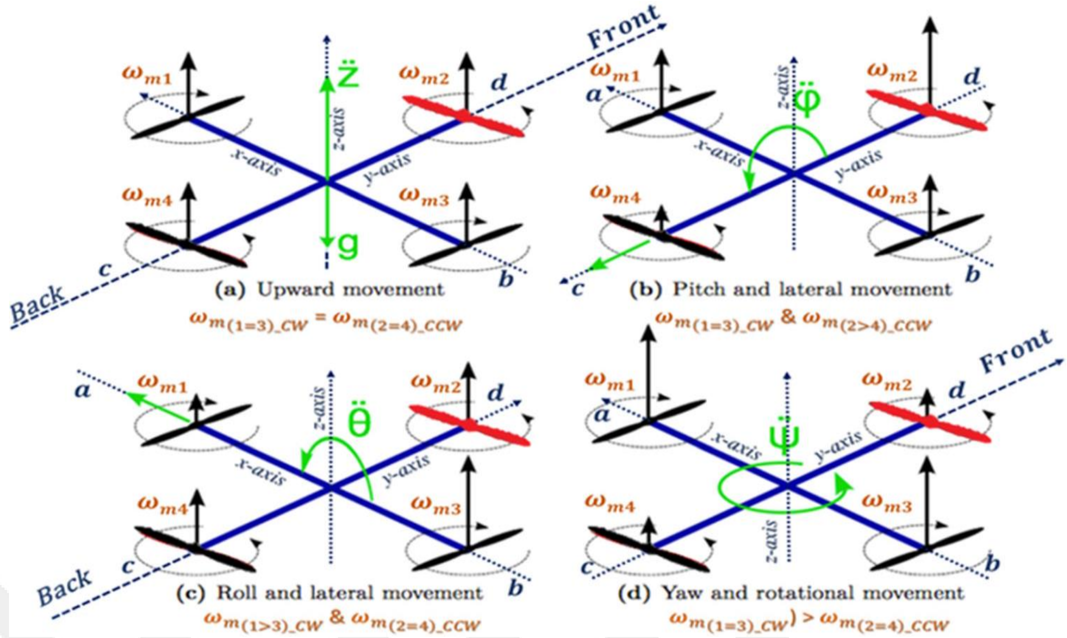

Figure 3.6 Plus configured quadcopter motion (Moad *et al.* 2021)

In the "X" configuration, shown in Figure 3.7, the four rotors of the quadcopter are arranged in the shape of an X. The front-left and rear-right rotors form one diagonal, while the front-right and rear-left rotors form another diagonal. This configuration is widely used in various commercial and recreational quadcopters. Advantages of the "X" Configuration are firstly, the "X" configuration offers increased agility and maneuverability. The diagonal motor arrangement allows for faster movements and more responsive flight control, making it suitable for applications that require quick and precise maneuvers. Secondly, the motor placement in an "X" configuration allows for a more compact frame design. This makes it suitable for smaller-sized quadcopters, where space efficiency is crucial. Lastly, the "X" configuration provides a balanced distribution of thrust. The diagonally opposing rotors generate equal torque around the quadcopter's center, resulting in better stability during yaw movements (rotational control) (Moad *et al.* 2021).

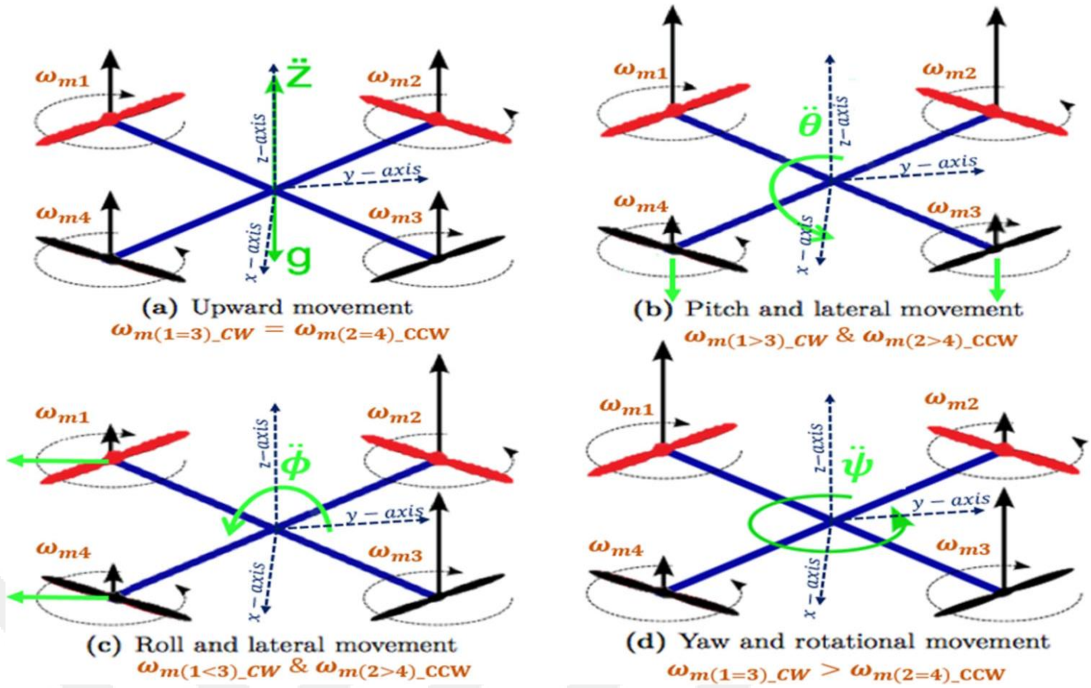

Figure 3.7 Cross configured quadcopter motion (Moad *et al.* 2021)

Both the "+" and "X" configurations have their advantages and are commonly used in various quadcopter designs. The choice between these configurations depends on factors such as the intended application, desired flight characteristics, payload requirements, and design preferences. It's important to note that regardless of the configuration, quadcopters rely on sophisticated flight control systems and sensors, including gyroscopes, accelerometers, and flight controllers, to maintain stability, adjust rotor speeds, and enable precise control during flight (Robert *et al.* 2016).

3.2.2 Movement of quadcopter

Quadcopter movement encompasses the various maneuvers that a quadcopter can execute in the air. As aircraft equipped with four rotors, quadcopters generate lift and control their flight direction through these rotors. Their versatile design and control capabilities enable them to perform a wide range of movements. Quadcopters can maintain a stable position in mid-air by adjusting the speeds of their four rotors, allowing them to hover in place without horizontal movement. By uniformly increasing or decreasing the rotor speeds, a quadcopter can ascend or descend vertically. To achieve forward, backward, or sideways motion, the speed of the rotors on one side is altered relative to the other side. For example, to move forward, the speeds of the rear rotors are increased relative to the front rotors, tilting the quadcopter forward and generating thrust in the desired direction (Abdulaziz 2022).

Quadcopters are also capable of rotating around their yaw axis, known as the z-axis. This is achieved by increasing the speed of two diagonally opposite rotors while decreasing the speed of the other two, causing the quadcopter to spin either clockwise or counterclockwise. It is important to note that quadcopters depend on sophisticated flight controllers and stabilization systems. These systems either autonomously perform these movements or enable human pilots to control them accurately and safely (Abdulaziz 2022).

3.2.3 Aerodynamic of quadcopter

Quadrotors are composed of propellers with two or more blades and a center hub that fits snugly onto the motor rod. Due to their design, accelerating the motor generates a push, forcing the vehicle to rise in the corresponding direction. This is because the propellers are the sole sources of aerodynamic loads on the quadrotor. To achieve effective flight, these components must be carefully selected for their size, weight, and material. For example, equipping an actuator with a larger propeller would increase the size of the stream tube, which in turn enhances the flying speed but also requires more power. Therefore, the first step in selecting an appropriate propeller for a quadrotor involves determining the thrust and drag coefficients of the blades. Figure 3.8 illustrates a three-dimensional model of the quadcopter (Zafer 2020).

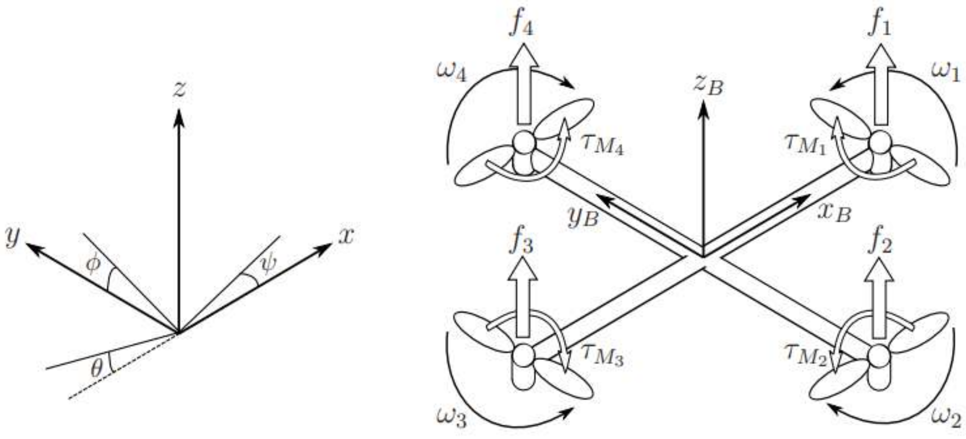

Figure 3.8 Quadcopter model (Teppo 2011)

The thrust moment can be calculated by the flowing Equation (3.1)

$$\mathrm{Ti} = \mathrm{K}\Omega_i^2 \tag{3.1}$$

Where Ti is the thrust moment for the corresponding brushless DC (BLDC) motor i, Ω_i is the angular speed of the BLDC motor i and K is a constant that represents either the thrust factor b or the drag factor d. The K constant is chosen according to the desired orientation of the Quadrotor (Zafer 2020).

The thrust and drag factor can be calculated as in Equation (3.2) and Equation (3.3)

$$\mathrm{b} = C_T \rho D^4 \tag{3.2}$$

$$\mathrm{d} = C_T \rho D^5 \tag{3.3}$$

Where d is the diameter of the region the propeller sweeps, ρ is the air density, and C_T is the thrust coefficient. Euler's Equation (3.4) to Equation (3.9) of motion is used to provide the whole mathematical model for the quadrotor as:

$$\ddot{x} = \frac{1}{m}(\sin\ \psi \sin\ \phi + \cos\ \psi \sin\ \theta \cos\ \phi)U_1 \tag{3.4}$$

$$\ddot{y} = \frac{1}{m}(-\cos\ \psi \sin\ \phi + \sin\ \psi \sin\ \theta \cos\ \phi)U_1 \quad (3.5)$$

$$\ddot{Z} = \frac{1}{m}\cos\ \theta \cos\ \phi U_1 - g \quad (3.6)$$

$$\ddot{\phi} = \left((I_x - I_z)/I_x\right)\dot{\theta}\dot{\psi} - (J_r/I_x)\dot{\theta}\Omega_r + (l/I_x)U_2 \quad (3.7)$$

$$\ddot{\theta} = \left((I_z - I_x)/I_y\right)\dot{\phi}\Psi + -(J_r/I_y)\dot{\phi}\Omega_r + \left(l/I_y\right)U_3 \quad (3.8)$$

$$\ddot{\Psi} = \left(\left(I_x - I_y\right)/I_z\right)\dot{\theta}\dot{\phi} + (1/I_z)U_4 \quad (3.9)$$

Where U_1 represents the overall thrust produced by the four rotors, and U_2, U_3, and U_4 represent the roll, pitch, and yaw thrusts, respectively. In the Quadrotor equation, m stands for mass, g for gravitational acceleration, l for the distance from the motor to the center of mass, J_r for moment of inertia, and I_x, I_y, and I_z for the moment of inertia in the x, y, and z axes for the entire body (Zafer 2020). The system input signals, which are characterized by the addition and subtraction of the four separate actuators, may be used to derive the required control action, as indicated in the following Equations (3.10) to (3.13).

$$U_1 = b(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2) \quad (3.10)$$

$$U_2 = b(-\Omega_2^2 + \Omega_4^2) \quad (3.11)$$

$$U_3 = b(-\Omega_3^2 + \Omega_1^2) \quad (3.12)$$

$$U_4 = d(-\Omega_1^2 + \Omega_2^2 - \Omega_3^2 + \Omega_4^2) \quad (3.13)$$

Ω_r is the relative speed of the motors. Ω_1 , Ω_2 , Ω_3, Ω_4 are the speeds of the 1st, 2nd, 3rd and 4th motors, as shown in the flowing Equation (3.14) respectively.

$$\Omega_r = \Omega_1^2 - \Omega_2^2 + \Omega_3^2 - \Omega_4^2 \tag{3.14}$$

4. MATERIALS AND METHODS

4.1 Brushless DC Motor

Brushless DC motors (BLDC motors) are electric motors that operate using direct current (DC) but eliminate the need for the brushes and commutators found in traditional brushed DC motors. Renowned for their efficiency, reliability, and smooth operation, BLDC motors find uses in robotics, aerospace, automotive, and consumer electronics. Unlike brushed motors, BLDC motors employ electronic commutation for rotation control. They excel in efficiency, as the absence of brush friction results in less heat generation and an extended lifespan. The reduced need for wear-prone components enhances their reliability and minimizes maintenance requirements. With high power density, BLDC motors are well-suited for space-constrained applications. Electronic commutation ensures quiet and smooth operation without 'cogging,' and these motors provide precise speed control, maintaining consistent speeds under varying loads. Their applications span across industrial automation, electric vehicles, drones, cooling fans, and more. BLDC motors can be either sensor-based, using position sensors, or sensorless, relying on algorithms to determine rotor position. Electronic control, via motor drivers or controllers, governs the timing of coil current for optimal efficiency. Most BLDC motors feature a three-phase setup that generates a rotating magnetic field (Padmaraja 2003).

4.2 Propeller

The drone's propeller plays a crucial role in generating the required thrust for lifting the drone off the ground and sustaining its flight. Drones generally feature multiple propellers, often in pairs, attached to arms extending from the central body. These propellers rotate swiftly to produce the necessary airflow and lift. Consumer drones usually have four propellers in a quadcopter setup, although other variations like hexacopters or octocopters may have more or fewer propellers. These propellers can rotate either clockwise (CW) or counterclockwise (CCW). For stability, drones typically employ two pairs of propellers that spin in opposite directions, effectively neutralizing the rotational forces generated by the propellers and maintaining steady flight (Darmeli *et al.* 2016).

Constructed from lightweight and durable materials like plastic or carbon fiber, drone propellers achieve a balance between strength, flexibility, and weight. Propellers come in different sizes and pitches; size denotes the propeller's diameter, and pitch indicates how far it would travel in one complete rotation through a solid substance. This variety in size and pitch allows for optimization of thrust and efficiency to suit specific drone designs and purposes. Regular inspection and maintenance are essential for safe and efficient flight. Damaged or imbalanced propellers can lead to reduced performance and flight instability. Proper balancing is vital to prevent vibration and excess stress on the drone's motors. Handling drone propellers with care, especially when the drone is powered on, is crucial to avoid potential injuries. Adherence to the safety guidelines provided by the drone manufacturer is essential. Enthusiasts might upgrade their propellers for improved performance, flight time, or reduced noise levels, although such changes may require adjustments to the drone's flight controller settings to ensure stable operation. In essence, drone propellers are fundamental components that influence flight characteristics, stability, and overall performance. An adequate understanding of their operation and appropriate care is essential for safe and enjoyable drone usage (Andria *et al.* 2018).

4.3 Electronic Speed Controller

An Electronic Speed Controller (ESC) designed for brushless motors functions as a tool that manages the brushless electric motor's velocity, orientation, and power provisioning. ESCs are vital constituents in a range of uses, including drones, remote control cars, boats, and similar applications. They oversee the electrical signals originating from the motor controller and regulate the flow of current and voltage supplied to the motor's coils, facilitating meticulous command over the motor's speed and overall functionality. When opting for an ESC suitable for a brushless motor, it becomes essential to factor in variables such as the motor's voltage and current requisites, alongside the specific needs of the given application. ESCs are available in assorted dimensions and current capacities to match distinct motor varieties and power thresholds. It's imperative to verify that the ESC's specifications harmonize with the motor chosen for the task (Bum-Su *et al.* 2018).

Propellers has been removed during ESC calibration. Before starting calibration, ESCs had not have a Lipo battery connection

4.3.1 Calibration Method-1

This calibration process updates all Electronic Speed Controllers (ESCs) by setting a maximum (2000 microseconds) and minimum (1000 microseconds) Pulse Width Modulation (PWM) input from the flight controller, operating at a constant frequency of 50 Hz. As a result of this calibration, all ESCs and motors on board the drone will respond uniformly to the inputs from the flight controller across the entire range of input values. This uniformity ensures synchronized and stable responses from all motors during flight operations.

4.3.2 Calibration Method-2

In Calibration Method-2, the calibration of an Electronic Speed Controller (ESC) is achieved through a defined sequence of steps. The process begins with the opening of the Lipo connection of the ESC. Following this, the maximum Pulse Width Modulation (PWM) is applied. The next step involves reconnecting the Lipo connection as outlined in the preceding step. After this reconnection, the battery is disconnected and then reconnected. At this juncture, it's necessary to wait for the ESC to emit a melody. Once the melody has concluded, the minimum PWM should be applied. Adherence to these steps ensures the successful calibration of the ESC.

4.3.3 Calibration Method-3

In Calibration Method-3, a straightforward procedure is employed to calibrate an Electronic Speed Controller (ESC). The process is initiated by disconnecting the ESC from the Lipo battery. Following this disconnection, the maximum Pulse Width Modulation (PWM) is sent to the ESCs. After completing this step, the ESC is reconnected to the Lipo battery. Powered while receiving the maximum PWM signal, the ESC enters calibration mode, emitting a series of beeps for a brief period. Upon the cessation of the beeping by the motors, the minimum PWM is then given promptly. The calibration process's successful completion is indicated by the sounding of another beep.

4.3.4 Calibration Method-4

Calibration Method-4 is recognized as a detailed process that has been designed for the calibration of Electronic Speed Controllers (ESCs). The ESCs should first be disconnected from the Lipo battery. Subsequently, the maximum Pulse Width Modulation (PWM) should be sent to the ESCs. Following this, the ESCs are to be reconnected to the Lipo battery. Upon reconnection, a sequence of tones, "beep1 beep2 beep3," should be audible, indicating the correct functioning of the power supply. A pause of approximately 2 seconds will be followed by a "beep beep" sound, which serves as confirmation of the maximum PWM being correctly received. The next step involves sending the minimum PWM to the ESC, an action that will trigger several beeps. These beeps correspond to the number of lithium battery cells, such as 3 beeps for a 3-cell LiPo battery. A long beep will then be heard, signifying the correct reception of the Minimum PWM. Once these steps have been completed, the ESCs are considered to be well calibrated and are ready for testing.

The calibration process is particularly important for low-cost Electronic Speed Controllers (ESCs) due to the wide variance in their input response. During ESC calibration, it's crucial to either remove the propellers or ensure the motors do not turn. The Lipo battery must be disconnected. If power is inadvertently applied to the ESC during calibration, or if the ESC does not properly support the calibration sequence, the ESC might respond to the PWM input by running the motor at maximum speed, which could lead to accidents. Figure 4.1 illustrates the calibration model in Simulink.

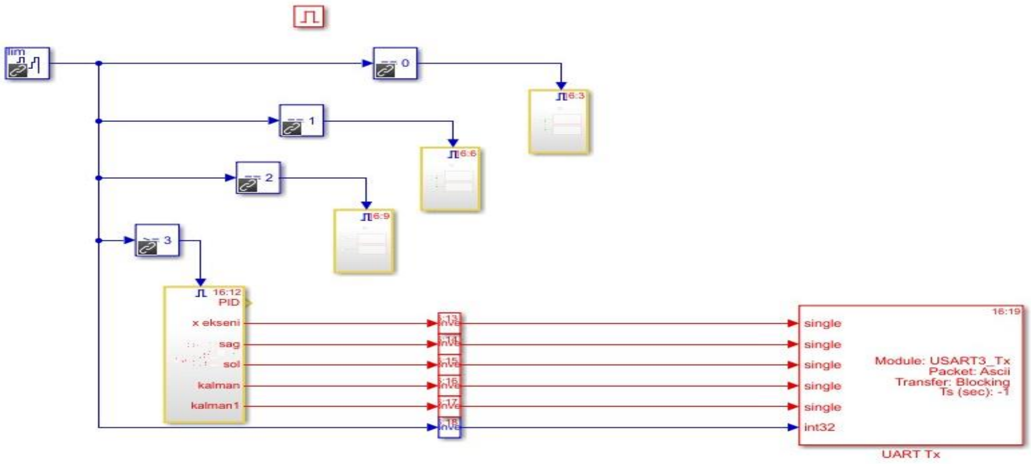

Figure 4.1 Calibration model

4.4 Lithium Polymer Battery

Lithium Polymer battery which is a type of rechargeable battery based on lithium-ion technology and uses a polymer electrolyte. These batteries are prevalent in various electronic devices such as drones, RC vehicles, laptops, and smartphones. Lipo batteries are notable for their high energy density, which allows for longer usage between charges, and their flexible shapes, making them suitable for a wide range of applications. They also offer diverse options in terms of voltage and capacity, and they are capable of fast charging. However, they require careful handling due to their sensitivity to overcharging and other potential risks. Balancing during charging is a common practice to ensure consistency across all cells in the battery. It is crucial to adhere to the manufacturer's guidelines for charging, using, and storing these batteries to ensure both safety and longevity. In summary, while Lipo batteries provide high energy density and quick charging capabilities, they necessitate cautious usage to avoid potential hazards (Chang *et al.* 2016).

4.5 STM32F407 Discovery

The Microcontroller STM32F407 is a low-cost, highly scalable microcontroller that efficiently streamlines the hardware design and development environment. It is also easy to program systems remotely, utilizing a large amount of Ethernet bandwidth. The remote monitoring system offers high test accuracy, strong real-time performance, and quick speed through actual test validation (Taoren 2019).

Outfitted with an STM32F407VG microcontroller, it employs the ARM Cortex-M4 core. This microcontroller ensures potent processing and incorporates numerous built-in peripherals. It usually incorporates Flash memory for program storage and SRAM for data storage, catering to application development requirements. The board encompasses various hardware peripherals, including GPIO pins, timers, ADCs, DACs, communication interfaces like UART, SPI, I2C, USB, and more. Supplementary components like LEDs, push-buttons, and possibly a display are integrated to enhance learning, prototyping, and debugging experiences. Featuring power supply circuitry, the board can be powered via USB or external sources. Often housing an integrated ST-Link debugger and programmer, it facilitates direct application programming and debugging. STMicroelectronics provides the comprehensive STM32CubeIDE, which furnishes tools, libraries, and examples for aiding software development (Cem 2022). We used it instead of Arduino because of the Arduino responding were a little bigger than we expected. Difference between the transmission period and reception period are 1.2 second as shown in the Figure 4.2.

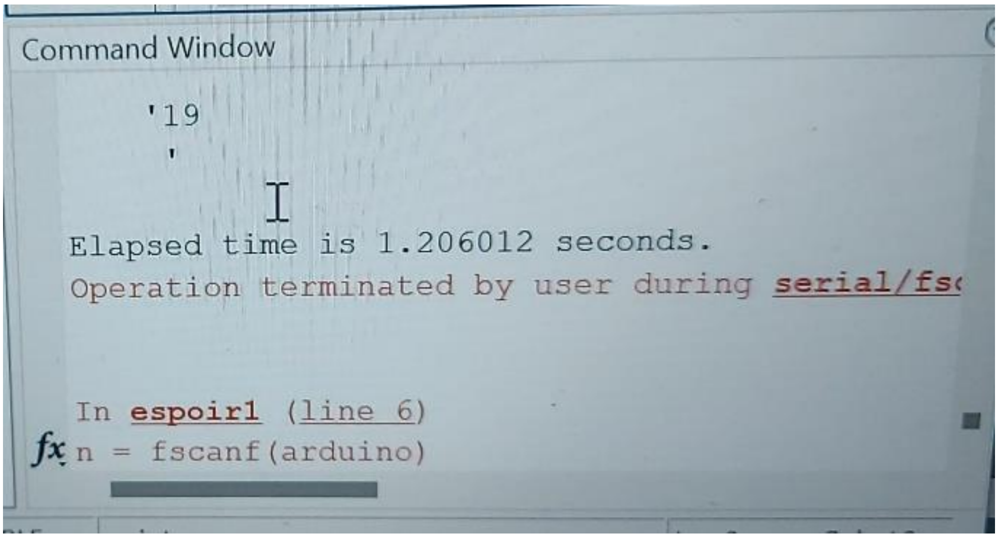

Figure 4.2 Arduino-Matlab serial communication

4.6 FT232 USB

The FT232 is an integrated circuit (IC) developed by FTDI that serves as a USB-to-Serial converter. It enables devices with USB interfaces, like computers, to communicate with devices using traditional serial ports. The FT232 bridges the gap between these communication protocols, allowing seamless data exchange and interaction. Key features include translation of USB and serial data, driver support for various operating systems, configurability for different communication parameters, and versatility across applications. The FT232 is a crucial tool for connecting legacy serial devices to modern USB-equipped systems, enhancing compatibility and efficient electronic communication (Anindita 2012).

4.7 Control Strategy Algorithm for a Quadcopter

Controlling a quadcopter involves managing multiple actuators (propellers) to achieve desired flight characteristics such as stability, maneuverability, and altitude control.

4.7.1 Measurement

To monitor and control a quadcopter, it's crucial to use onboard sensors like accelerometers, gyroscopes, magnetometers, and barometers. These sensors measure linear acceleration, angular rates, linear accelerations, and altitude. The data collected includes the quadcopter's orientation, angular rates, linear accelerations, and altitude, which are essential for stable and controlled flight. Including a barometer can also provide altitude information.

4.7.2 State estimation

To improve the accuracy and reliability of quadcopter state estimates, it is crucial to use sensor fusion techniques like Kalman filters or complementary filters. These filters combine data from different sensors, such as position, velocity, orientation, and angular rates, to provide a more accurate estimate of the quadcopter's current state. The Kalman filter is known for filtering out noise and combining various sensor inputs over time, while the complementary filter is simpler and often used for combining high-frequency data from gyroscopes with low-frequency data from accelerometers and magnetometers. Fusing data from multiple sensors, such as accelerometers, gyroscopes, magnetometers, and possibly barometers, compensates for individual sensor limitations, leading to a comprehensive understanding of the quadcopter's behavior and environment.

4.7.3 Controller design

To effectively manage and control a quadcopter, a hierarchical control structure has been designed, consisting of multiple control loops with different objectives. Each loop can focus on specific aspects of the quadcopter's operation, such as stabilization, navigation, or trajectory tracking. An Inner Loop Controller for Stabilization is developed to stabilize the quadcopter's attitude, including roll, pitch, and yaw. Attitude errors are calculated to understand the difference between the desired and estimated attitudes. A control algorithm, such as a Proportional-Integral-Derivative (PID) controller, nonlinear controller, or adaptive control, is used to compute control signals for each actuator, such as motors and propellers. The choice of control algorithm depends on the requirements for precision, responsiveness, and robustness of the control system. Finally, the computed control signals are translated into motor commands to adjust motor speed or thrust, ensuring the quadcopter responds accurately to control inputs for stability and following the desired flight path.

4.7.4 Motor control

To manage a quadcopter's flight dynamics effectively, it is essential to apply motor speed or thrust commands calculated in previous steps for each motor/propeller. These commands dictate adjustments in motor speed or thrust levels, ensuring the desired attitude, altitude, and trajectory. This helps identify discrepancies between commanded and actual motor behavior, ensuring they maintain the necessary thrust and speed for stable flight. Regular monitoring helps in early detection of potential issues, allowing for timely interventions to maintain flight safety and efficiency.

4.7.5 Iteration and adaptation

To ensure the quadcopter's optimal performance and stability, it is crucial to execute the control loop in a continuous, closed-loop manner, involving measurements, state estimation, control calculation, and motor control. This process ensures real-time responsiveness and adaptability to changing conditions during flight. Regularly monitoring the quadcopter's flight characteristics, such as stability, motion smoothness, and adherence to desired flight behaviors, helps identify areas where performance may deviate from expected outcomes. This allows for timely adjustments to control algorithms or parameter settings. The goal is to maintain stable flight, achieve smooth motion, and operate according to predefined flight plans. Regular adjustments and fine-tuning of the control system are essential to coping with environmental variations, payload changes, and other factors that might influence the quadcopter's performance.

4.7.6 PID controller

A PID controller is a crucial feedback control algorithm in engineering and industrial processes. It maintains stability and precise control by continuously adjusting an actuator based on the measured error between the desired setpoint and the actual process variable. The controller consists of three components: proportional, integral, and derivative. The proportional component produces an output proportional to the error, while the integral component sums up past error values over time. The derivative component predicts future error behavior and anticipates the output needed to counteract it, providing damping and stability. By combining these components, the PID controller can effectively respond to various types of errors and disturbances in a control system. The controller's output is calculated using Equation 4.1.

$$\text{PID} = \text{Kp} * \text{Error} + \text{Ki} * \text{Integral of Error} + \text{Kd} * \text{Derivative of Error} \qquad (4.1)$$

Tuning the PID controller involves adjusting the three gains, Kp, Ki, and Kd, to achieve the desired performance. Proper tuning is crucial to ensure stability, minimize overshoot, and respond quickly to changes in the setpoint or disturbance. The optimal tuning values depend on the specific process and application. Various methods, such as Ziegler-Nichols, Cohen-Coon, or trial-and-error, can be used for tuning the PID controller to achieve the desired response (Hari 2012).

4.7.7 Extended kalman filter

The extended Kalman filter is a modified version of the standard Kalman filter that can be applied when the system and/or the measurement models are nonlinear. Equation (4.2) and Equation (4.3) are respectively the nonlinear differential (for the continuous case) and difference (for the discrete case) equations that describe the system model:

$$\dot{x} = f(x(t), u(t) + w(t) \tag{4.2}$$

$$x_k = \Phi_{k-1}\,(x_{k-1}, u_{k-1}) + w_{k-1} \tag{4.3}$$

The Equation 4.4 and 4.5 describe nonlinear measurement model for the continuous and discrete time version are respectively:

$$\mathrm{z(t)} = \mathrm{h}\big(\mathrm{x(t)}\big) + \mathrm{v(t)} \tag{4.4}$$

$$\mathrm{z}_k = h_k(x_k) + v_k \tag{4.5}$$

The nonlinear equations are used directly for the state prediction and to compute the measurement residual, so Equation (4.6), (4.7) and (4.8) become respectively:

$$\hat{x}_k(-) = \Phi_{k-1}(\,\hat{x}_{k-1}(+), u_{k-1}) \tag{4.6}$$

$$\hat{x}_k(+) = \hat{x}_k(-) + \bar{K}_k[\, z_k - h_k(\hat{x}_k(-))] \tag{4.7}$$

$$\dot{\hat{x}} = f(\hat{x}_k(t), u(t)) + \bar{K}_k(t)[z(t) - h(\hat{x}(t))] \tag{4.8}$$

To achieve attitude control in a quadcopter, it typically involves adjusting motor speeds and orientations based on sensor feedback from an Inertial Measurement Unit (IMU) and other sensors. The control algorithms aim to minimize deviations in attitude and achieve the desired orientation. This enables the quadcopter to respond to user commands and adapt to environmental changes while maintaining stable flight. A PID controller and an extended Kalman filter are used to stabilize the quadcopter in the desired attitude. The LIS 302DL accelerometer data is received and processed using an STM32F4 discovery board, as shown in Figure 4.3.

Figure 4.3 STM32F4 discovery

The host model, depicted in Figure 4.4, allows for any modifications detected by the accelerometer sensor to be received from the STM32F4 card.

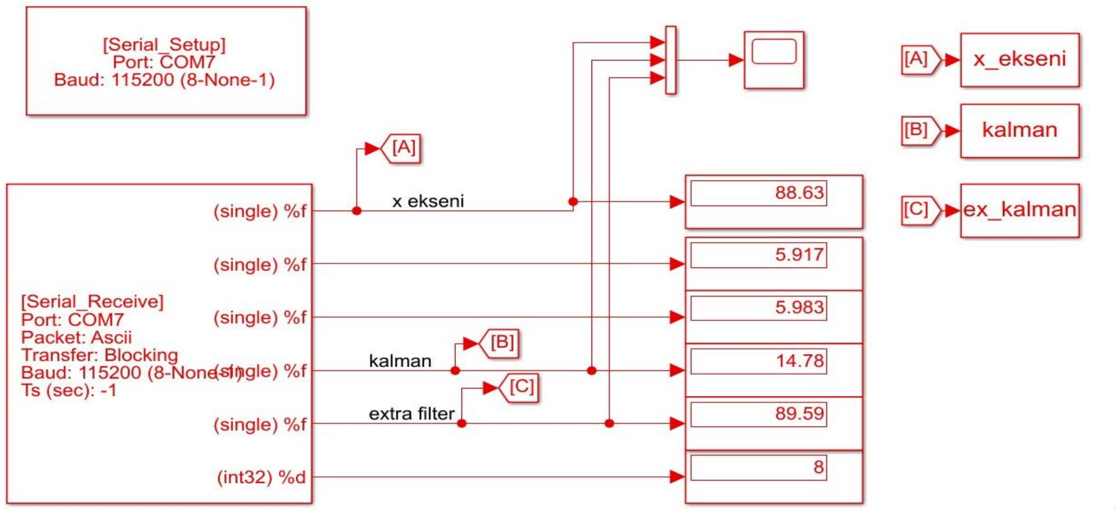

Figure 4.4 Host model for receiving from the STM32F4 discovery

On the other hand, transmission is facilitated by the Transmitter model in Figure 4.5. Figures 4.6 and 4.7 illustrate the extended Kalman filter parameters and the Simulink model for tuning the quadcopter with the PID controller and the aforementioned filter.

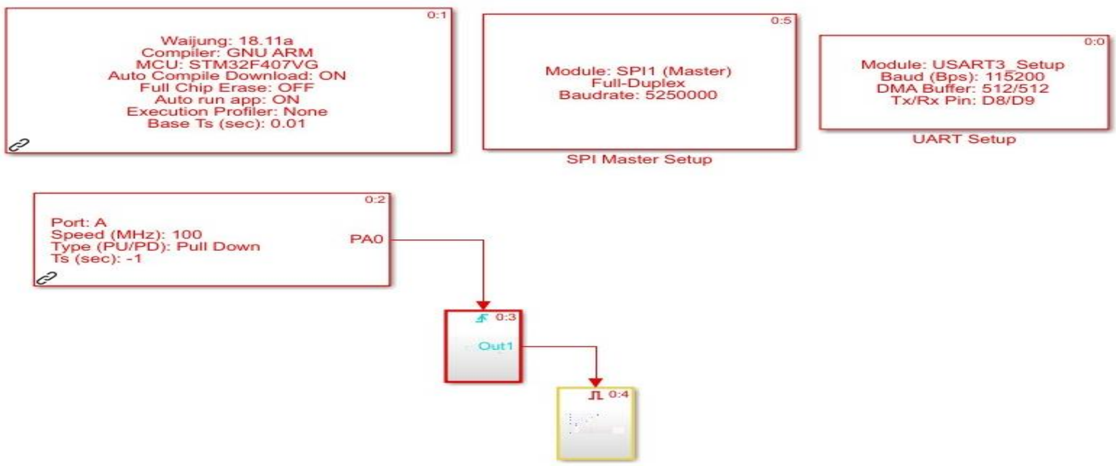

Figure 4.5 Transmitter model from Matlab to STM32F4 discovery

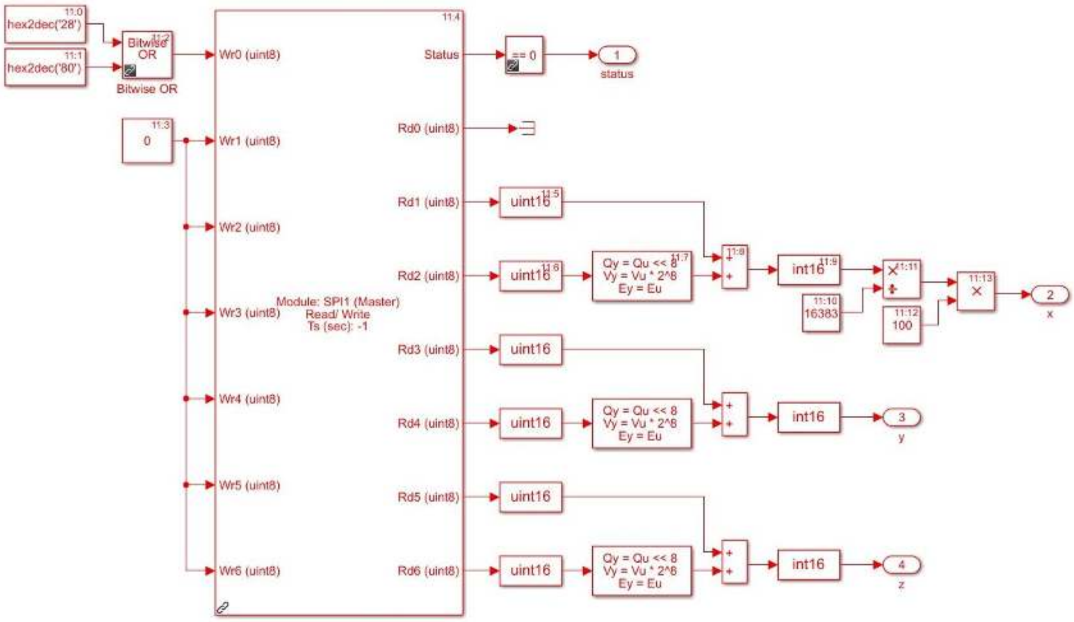

Figure 4.6 Extended Kalman filter

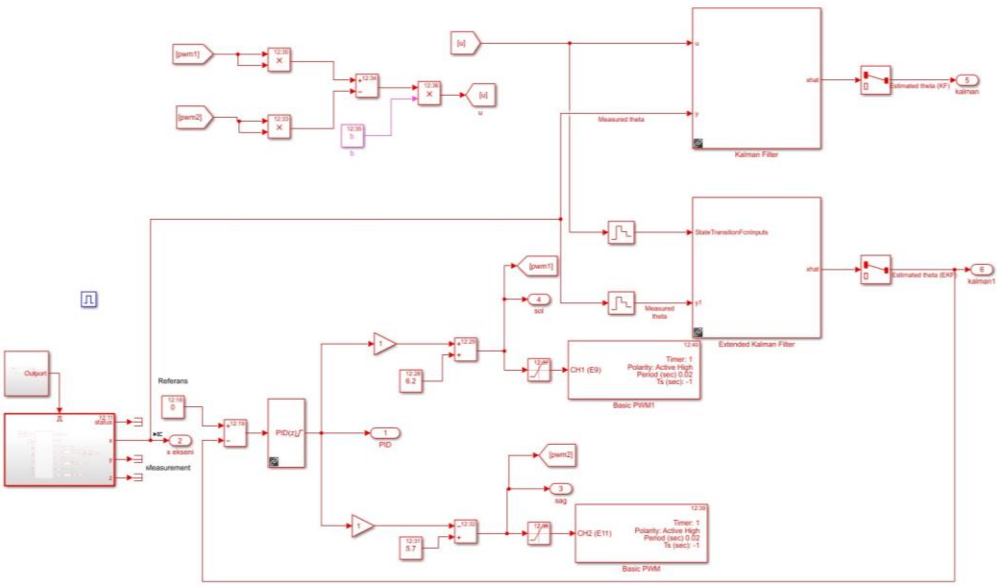

Figure 4.7 Tuning quadcopter's motor with PID controller with extended kalman filter

5. RESULTS AND DISCUSSION

The main difference between a signal processed by an Extended Kalman Filter (EKF) and one without any filter lies in the quality and accuracy of the resulting signal. An EKF is designed to reduce the effects of noise and measurement errors, providing a filtered signal that is more resistant to random fluctuations or measurement inaccuracies. In contrast, a signal without any filters retains all the noise inherent in the raw data. The EKF estimates the underlying state of a dynamic system in addition to filtering out noise, generating a more informative signal by integrating observations with the system's dynamic model. An unfiltered signal, being a direct representation of raw data, does not offer such estimation. Employing an EKF allows access to an estimated state of the system, which is valuable for understanding system behavior, making predictions, or controlling the system. This additional information is missing in an unfiltered signal. Due to its consideration of system dynamics and measurement errors, the signal obtained through EKF filtering is expected to be more accurate and precise. Without filtering, the signal may contain more errors and uncertainties, rendering it less reliable for analysis or decision-making.

EKFs are commonly used in sensor fusion, which involves combining data from multiple sensors to gain a more accurate and comprehensive understanding of the system. Unfiltered inputs from individual sensors might not adequately capture the system's context, particularly in nonlinear systems where simple averaging or linear filters would fall short. Handling nonlinearities and uncertainty becomes challenging without filtering. In real-time applications such as autonomous navigation, robotics, or control systems, an EKF can provide a more stable and accurate representation of the system state, crucial for safe and reliable operation. An unfiltered signal may not be sufficiently accurate for some applications. While EKFs offer superior state estimation and filtering capabilities, they are computationally more intensive. An unfiltered signal, although less computationally demanding, provides less precise and reliable information.

So, the difference between a signal filtered by an Extended Kalman Filter and one without any filter is significant in terms of signal quality. The filtered signal is expected to be more accurate, reliable, and informative, thanks to noise reduction, state estimation, and the incorporation of system dynamics. The choice between using filtered and unfiltered signals depends on the specific application's requirements for accuracy and noise reduction. The integration of both the PID controller and the EKF, as depicted in Figure 5.1, offers advantages wherein the PID controller maintains the desired state of the drone, while the EKF ensures accurate state estimates even amidst sensor noise and nonlinear dynamics..

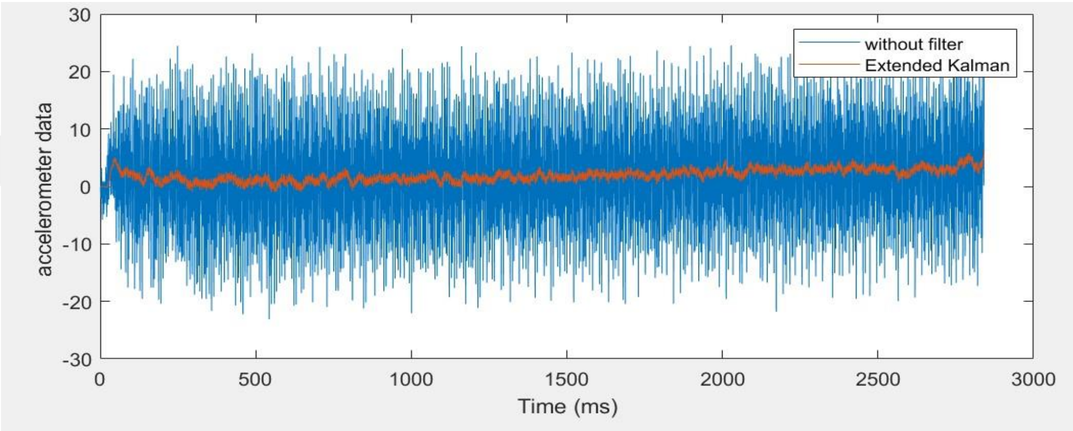

Figure 5.1 Difference between filtred signal with the extended Kalman and raw signal in terms of stablity

The EKF can also estimate unmeasured states, such as wind speed or external disturbances, which can be used by the PID controller for more robust control as shown Figure 5.2.

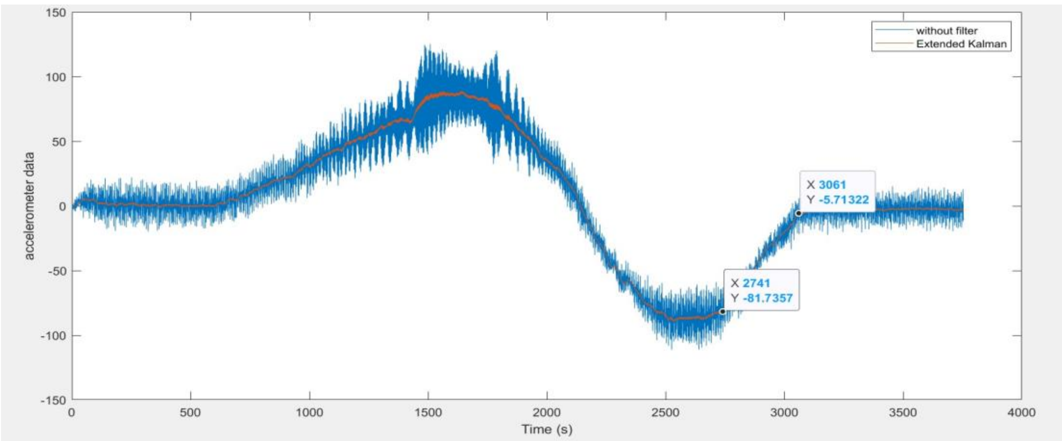

Figure 5.2 System response against error

The EKF can adapt to changing environmental conditions or system parameters, making the drone control system more versatile as shown in Figure 5.3. If one component experiences issues or failures, the other can help maintain control and stability, increasing the overall reliability of the drone.

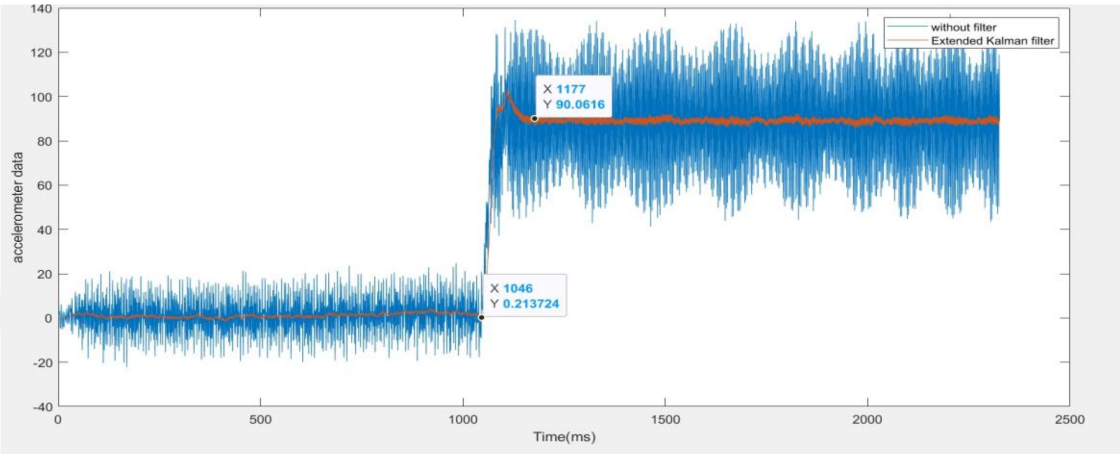

Figure 5.3 Response of the system with the attitude changes

Careful tuning of the PID gains and configuring of the EKF to suit the specific drone and sensor setup have been involved in the implementation of a PID controller with an EKF for drone control. The choice of sensors, sensor fusion algorithms, and control gains is dependent on the application and the drone's intended use, be it aerial photography, autonomous navigation, or any other purpose. Optimal drone control requires proper integration and calibration of these components.

6. CONCLUSIONS AND RECOMMENDATION

The integration of a PID controller and an Extended Kalman Filter (EKF) in quadcopter control is a significant advancement in unmanned aerial vehicle (UAV) technology. The PID controller is known for its simplicity, efficiency, and real-time responsiveness, making it essential for fundamental quadcopter functions like stabilization, altitude management, and orientation control. Its ability to quickly respond to changes in the quadcopter's environment and adjust accordingly is crucial for maintaining steady flight. The EKF, on the other hand, is instrumental in accurately estimating the state of the quadcopter, excelling in complex and dynamically changing environments where precise determination of position, velocity, and orientation is critical. Its strength lies in processing noisy or imperfect sensor data and effectively managing nonlinear dynamics often encountered in UAV operations. When combined, these two systems complement each other, resulting in enhanced overall performance and adaptability. However, successful implementation of this dual-control system requires careful tuning, extensive testing, sensor data reliability, and adaptability to various environments and operational requirements. Continuous improvement and updating of the control systems are also essential to keep pace with technological advancements and evolving operational needs. The fusion of a PID controller and an EKF in quadcopter control represents a sophisticated approach to UAV control, enhancing the capabilities of quadcopters in traditional applications like aerial photography and videography but also extending their utility to more demanding tasks such as search and rescue operations and environmental monitoring. By adhering to recommendations for tuning, testing, sensor data reliability, environmental adaptability, and continuous improvement, the full potential of these advanced unmanned aerial vehicles can be realized.

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