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Design and Optimization of a Flight Controller for a Quadcopter System Using Extremum Seeking PID Control to Minimize Performance Cost Functions

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ABSTRACT
Conventional proportional-integral-derivative (PID) controllers have gained popularity in industrial automation and process control in recent years because of its efficacy for the majority of linear systems, simplicity, ease of design, and cheap maintenance costs. Conventional PID controllers, on the other hand, are known to function poorly in higher-order and time-delayed linear systems, nonlinear systems, and extremely complicated systems without accurate mathematical models. Auto-tuning and adaptive PID controllers are two examples of the improvements to traditional PID controllers that have been created recently to address these issues. The flight controller for a quadcopter-helicopter system was designed in this study using an extremum-seeking PID controller with the goal of minimising the cost function and identifying the ideal set of PID parameters. The study will start with the creation of the quadcopter UAV system's mathematical model, and then a simulation will be run to show how well the control strategy works. The outcome demonstrates that the controller was successful once the system reached stability in the minimum amount of time.
Keywords : [Controller, ExtremumSeeking ,PID, UAV, Stability]

I. INTRODUCTION

In a wide variety of applications, such as intelligence collection, surveillance, reconnaissance missions, power line inspections, aerial videography, search and rescue, and more, autonomous unmanned aerial vehicles, or UAVs, are becoming increasingly popular. Four rotors with two pairs of counter-rotating, fixed-pitch blades in the corners of the aircraft characterise a quadcopter, a type of rotary-wing unmanned aerial vehicle (UAV) (Khan NA. Jhanji NZ, Brohis, SM & Nayar, A. 2020). Quadcopters, in contrast to traditional fixed-wing aircraft, have special qualities that make them perfect for a range of uses. Vertical Take-Off and Landing (VTOL) capabilities, hovering ability, low-speed and low-altitude cruising, and aggressive manoeuvrability are some of the notable benefits over other UAV kinds.

With six output degrees of freedom (spatial movements) and four input forces (the push produced by each propeller), a quadcopter is an underactuated dynamic vehicle. Quadcopters use fixed-pitch rotors, as opposed to conventional helicopters with rotors that change pitch angles. A quadcopter's four motors' speeds, which can change in unison or in opposition, control its flight behaviour. A dynamic equation that models these inputs may forecast the quadcopter's orientation and position, offering crucial direction for creating a successful flight control plan.

The complexity and highly nonlinear nature of its vehicle dynamics, particularly in the presence of uncertainties and disturbances, are the main obstacles to the development of a quadcopter for advanced applications under flight conditions. The quadcopter's flight path control system, which is in charge of controlling, directing, and regulating the vehicle's dynamics to produce desired behaviour and performance, is frequently unstable and performs poorly as a result of these variables.

Traditional proportional-integral-derivative (PID) controllers have been created and used extensively in industrial automation and process control in recent years because of their effectiveness for the majority of linear systems, simplicity, ease of design, and cheap maintenance costs. In contrast, Xu and Y. Zhang (2023). Traditional PID controllers are known to function badly in higher-order or time-delayed linear systems, nonlinear systems, and particularly complex systems without accurate mathematical models. Auto-tuning and adaptive PID controllers are two ways that traditional PID controllers have been modified in recent years to meet these issues (Tang, P., J Dai, Y.; Chen, J. 2022).

Unmanned aerial vehicles (UAVs), sometimes referred to as drones, are aircraft that do not have a human pilot on board. While some UAVs can fly on their own with little to no assistance from humans, most are controlled from a ground station. Fixed wing and rotary wing are the two categories under which UAVs fall. The configuration of fixed wing aircraft is similar to that of aircraft used for both passenger and freight transportation. These units are lifted off the ground and given the ability to continue flying by the continuous forward development created by a propeller's rotation. High speeds and long distance flight are taken into account by the basic shape finish, which has a single, unbending wing across the body.

Applications like mapping and surveillance that cover large areas are ideal for this kind of automation. Additionally, certain fixed wing units are the perfect eye-in-the-sky for farmers. However, human helicopters and rotary wing UAVs are very similar. Both contain numerous propellers that raise the UAV and drive it in the desired direction. The number of propellers varies from one to six or even eight, but the basic idea is the same. Drones with rotary wings are great for jobs that need the UAV to move inside a certain region or remain motionless in one spot. They may, however, have a restricted range of motion. (C. Yin and others, 2014)

1.0 Quadcopters

An aerial vehicle with four rotors for lift, steering, and stabilisation is called a quadcopter. The quadcopter can fly vertically with more stability than other kinds of aerial vehicles. Because of its symmetric, cyclic structure, it avoids the torque problems that helicopters frequently encounter, which are caused by the main rotor. Its design also makes building and maintenance simpler.The military, engineers, researchers, and amateurs are among the groups that have taken notice of quadcopters and are investigating their possibilities in a variety of technical domains. Quadcopters, for example, are widely employed for data collecting and reconnaissance tasks, such as examining electrical power lines and looking for survivors in disaster regions. Certain commercially available quadcopters can transport small loads, including food and medical supplies, to far-flung locations that are inaccessible by conventional aircraft. Multi-copters have also been invented and constructed by numerous amateur radio operators. In recent years, quadcopter research has been carried out at prestigious colleges like as MIT. Other kinds of multi-copters, including octacopters, hexacopters, tricopters, and bicopters, are also in use in addition to quadcopters.

1.1 Stability and Flight Control of Quadcopter

As mentioned before, it is nearly hard to achieve stable flight in a multirotor aircraft without electrical help. The flight controller is the central component that houses all of the electronic systems. It consists of programmable software, a central CPU or microcontroller, and a variety of sensors that are used to identify the orientation, location, and status of the aircraft (C. De Paula et al., 2013). To control and stabilise the aircraft's flight dynamics, the flight controller incorporates flight control software that makes use of inputs from the radio transmitter and data from various sensors (Q. Xu and Y. Zhang, 2023).

In order to minimise the cost function and identify the ideal set of PID parameters, this study intends to apply an extremum-seeking PID controller in the design of a flight controller for a quadcopter-helicopter system. To show the usefulness and efficacy of the suggested control approach, a simulation will be conducted after the mathematical model for the quadcopter UAV system has been developed (Y. Zhang et al., 2022).

1.2 Quadcopter Flight Control

Four motors are uniformly spaced along the quadcopter frame to form a quadcopter. Pusher rotors are used by Motors 1 and 3 to rotate in a clockwise orientation. On the other hand, motors two and four use puller rotors to rotate counter-clockwise. About the quadcopter's centre, each motor generates thrust and torque. The net torque about the quadcopter's centre should ideally be zero, resulting in zero angular acceleration, because of the motors' opposite spinning reactions. Yaw stabilisation is no longer necessary as a result. By evenly increasing each motor's speed through throttle adjustments, a vertical force is produced. The quadcopter starts to rise in altitude when these vertical forces are greater than the Earth's gravitational pull (Khan, M. (2014)).

Increasing (or reducing) the speed of the front or back motors produces pitch. The quadcopter rotates along the x axis as a result. Only the pitch angle acceleration is altered because the left and right engines provide the same overall vertical push as hovering. The forces produced by the corresponding rotor are smaller than those produced by the back rotor as the front motor slows down. According to Muller M.W. and D. Adrea R. (2014), these forces lead the quadcopter to lean forward.

1.3 Quadcopter Stability Control

Wind and other environmental conditions are examples of external disruptions that can make it impossible for a drone to fly steadily on its own. In addition to controlling yaw, pitch, roll, and thrust, the main function of the flight control system (which includes the flight control board and software) is to identify any changes in the drone's orientation. The system determines the required adjustments to return the aircraft to its intended set-point as soon as a mistake is recognised (Kotarski, D. 2016). Onboard sensors, like an IMU system, are used by the flight control board (Zosimoveh, N., 2025). This includes an accelerometer and gyroscope, and it could also have other sensors like a camera to measure horizontal velocity or a barometer to measure altitude. A control loop is used to process the raw data from these sensors in order to compute errors and identify the necessary corrections. To accomplish this stability and control, an extremum-seeking based PID controller is used in this study (Arbab, N., et al. 2014).

II. METHODOLOGY

Dynamic Model of the Quadcopter Using Newton-Euler Equations

We commence by characterising the space in which these dynamics will be portrayed in the first stage of creating the vehicle dynamics. Six coordinates can be used to define the location of every point on the quadcopter, which is equivalent to a rigid body in a three-dimensional universe. Usually represented as (x, y, z), the first three coordinates show the location of the object's centre of mass (CG) in relation to an origin in the three-dimensional environment. To keep things simple, we'll adopt a flat-Earth model, which means the quadcopter has a constant gravity and operates above level terrain in a rectilinear coordinate system. Since the centre of mass and the centre of gravity (CG) are the same in this model, the terms can be used interchangeably (Y. Zhang, H. et al., 2022).

We must specify the quadcopter's orientation in space even if we are aware of its centre of gravity. We accomplish this by using the remaining three coordinates , which are known as Euler angles and reflect the vehicle 's orientation through three angles : (/, Θ, Ψ). Together with the position (x, y, z), these angles establish the quadcopter's overall state and describe how the vehicle rotates in three dimensions. We can locate each point on the quadcopter in relation to the centre of gravity by using the six coordinates—three for position and three for orientation. According to a rigid body assumption, there is a continuous link between all of the vehicle's mass points.

In contrast, points on the vehicle can move independently in a flexible body model, adding more complexity. The three position components (x, y, and z) are simple and represent distances in each of these directions. They can be aligned with North, East, and vertical height. The three orientation components (ʸ, Θ, and Ψ) are less obvious, though. Although orientation can be represented in a variety of ways, Euler angles and quaternions are the two most widely used techniques. We will use Euler angles to determine the quadcopter's equations of motion since they are the easiest to comprehend and offer important information about the system's behaviour.

Euler angles can have a drawback, though, in that they can be ambiguous for some orientations, meaning that the orientation is not uniquely defined by the three angles. This problem is called gimbal lock, and quaternions can help with it. Euler angles are typically chosen for output because of their simplicity, even though quaternions are frequently utilised in simulations and controllers for computational stability.The two coordinate frames in which the quadcopter will function will be introduced before we dive into Euler's Equations. With gravity pointing in the negative z-direction, the inertial frame is locked to the ground. The quadcopter's orientation determines the body frame, with the arms extending along the x and y axes and the rotor axes aligned along the positive z-direction. With this configuration, we can use Newton-Euler equations to model and study the quadcopter's behaviour.

2.1 Newton-Euler Approach for Quadcopter System

The differential equations that define the quadcopter system's dynamics are described via the Newton-Euler Approach. Consideration is given to the system with mass m and the body's inertia I.

The principal inertia axes coincide with the $\mathcal{F}$B coordinate axes because, assuming the quadcopter frame has a symmetrical structure, the four propulsor carriers are aligned with the XB and YB axes.

The diagonal matrix and the inertia matrix are equivalent.
Ixx=Iyy
I =

$$\begin{bmatrix} I_{XX} & 0 & 0 \\ 0 & Iyy & 0 \\ 0 & 0 & I_{ZZ} \end{bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.1)$$

However, the quadcopter dynamics is defined as:

$$A = \begin{bmatrix} mI_{3\times3} & 0_{3\times3} \\ 0_{3\times3} & I \end{bmatrix} \begin{bmatrix} V^B \\ \omega^B \end{bmatrix} + \begin{bmatrix} \omega^B \times (mV^B) \\ \omega^B \end{bmatrix} = \begin{bmatrix} f^B \\ \tau^B \end{bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.2)$$

v̇B is the linear acceleration vector
ωB is the angular acceleration vector
fB is the force vector acting on quadcopter
τB is the torque vector acting on quadcopter
all with the respect to the $\mathcal{F}$B.
Hence, the generalized force vector λ

$$\lambda = [f^B \quad \tau^B]^T = [F_x\ F_y\ F_z \tau_x \tau_y \tau_z]^T \ldots\ldots\ldots\ldots\ldots(2.3)$$

Equation (3.30) is best written as;

$$\mathbf{M_B}\ \dot{\nu} + \mathbf{C_B(v)}\ \mathbf{v} = \boldsymbol{\lambda} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.4)$$

However,
v̇ is the generalized acceleration vector

MB is the system inertia matrix

CB(**v**) is the Coriolis-centripetal matrix, all with the respect to the $\mathcal{F}$B.

The diagonal matrix that consists of the quadcopter mass and moments of inertia with respect to the coordinate axes of $\mathcal{F}$B is the inertia matrix of the quadcopter system.

The dynamics of the quadcopter are explained in $\mathcal{F}$B. The Coriolis-centripetal matrix is added to the model, improving it by including the centripetal force acting on the rotating body and the Coriolis effect, which influences the moving body in a rotating frame.

All rigid bodies to which the presumptions (symmetry and the same origin for $\mathcal{F}$B and COG) may be applied are generally covered by equation (2.3).The three parts of the force vector **λ** are the movement vector, the gyroscopic torque vector, and the gravity vector.

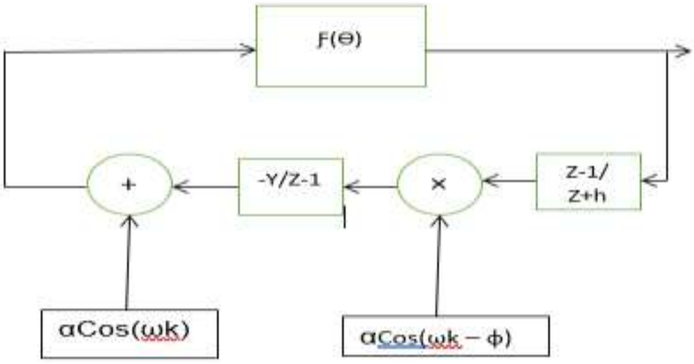

Figure 1: Block diagram of discrete extremum seeking scheme.

2.2 Simulation

We can now construct a simulation environment to test and observe the outcomes of different inputs and controllers since we have finished the equations of motion that describe the system's dynamics. We can rapidly create a simulator that uses Euler's method for solving differential equations to update the system state, even if there are more sophisticated approaches available (Bittar, A., et al, 2014). A function to calculate the rotation matrix R, values for all of our physical constants, and functions to translate an angular velocity vector ω into the derivatives of roll, pitch, and yaw and vice versa would also be required if we were to use MATLAB as our simulator.

A three-dimensional visualisation of the quadcopter that is updated while the simulation runs may then be created.

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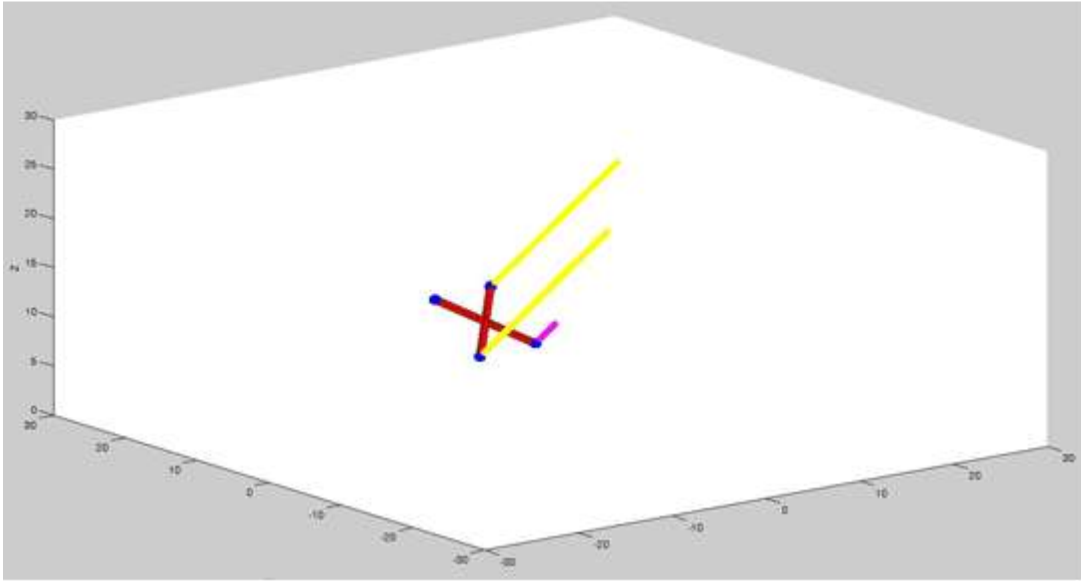

Figure 2: quadcopter in a three-dimensional visualization

In the quadcopter simulation, the bars above each propeller represent the relative thrust magnitudes, providing a rough indication of the thrust produced by each motor as shown in Figure 2.

2.3 Implementing Extremum seeking based PID tuning

We may develop a function that calculates the cost for a specified set of PID settings using our quadcopter simulation. A decent set of PID parameters can subsequently be obtained by minimising the cost function using our gradient descent method. By plotting the cost function against the number of iterations, we can confirm that our tuning strategy is effective and observe that the cost function is, in fact, decreasing and stabilising at a local minimum.As shown in Figure 3

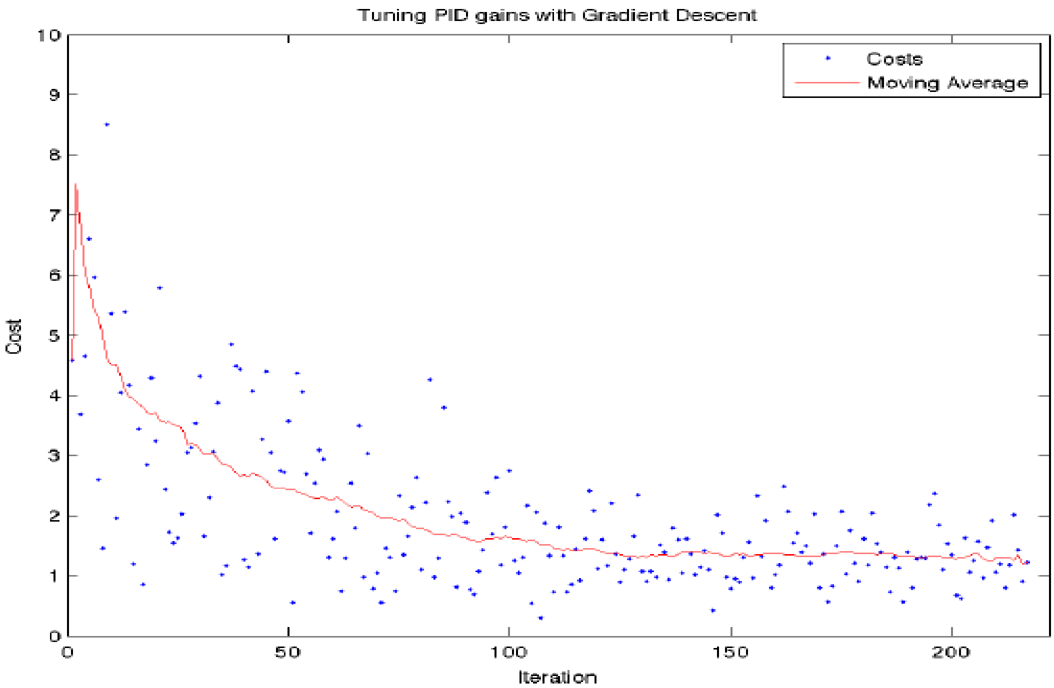

Figure 3: Tuning PID gains with Gradient Descent

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As seen in Figure 3, the cost function and moving average are represented as a function of iteration number. When the moving average's slope can be statistically indistinguishable from zero with a 99% confidence interval, tuning is done.

III. RESULT AND CONCLUSION

In this research work, the MATLAB/Simulink took in some input which represent the RPM of each motors and then the effects were visible on the model through the simulation.After developing the dynamic model, it was tested with some inputs, As observed in simulation, result obtained from the automatic tuned PID was better, making the flight control; suitable for real world purposes.

REFERENCES

[1]. Arbab, N., Dai, Y. and Syed, A. and Xu, X. (2014). “Stable Hovering Flight for a Small Unmanned Helicopter Using Fuzzy Control”, Mathematical Problems in Engineering, Vol. 2014, Article ID 208253.

[2]. Bittar, A., Figuereido H.V, Guimaraes P.V and Mendes A.C (2014). “Guidance software-In-the-loop simulation using X-Plane and Simulink for UAVs”, International Conference on Unmanned Aircraft systems (ICUAS), May 27-30, 2014, pp. 993-1002.

[3]. C., De Paula, G. V., Leandro, Marlio, C. B. (2013). Stability Control of a Quad-Rotor Using a PID Controller. Brazilian Journal of Instrumentation and Control. 45, 321 – 334.

[4]. Khan, M. (2014). Quadcopter Flight Dynamics. International Journal of Scientific and Technology Research, 3(8), 130–135.

[5]. Khan NA.Jhanji NZ, Brohis SM &Nayar A (2020).Use of UAV’s: Secure Communicationprotocol issues and challenges. Dronein Smart-cities, pp.37-55,Elvivier

[6]. Kotarski, D. (2016). Control Design for Unmanned Aerial Vehicle with Four Rotors. Interdisciplinary Description of Complex System Journal, 14(2), 236-245.

[7]. Muller M.W and D‟Adrea R. (2014). “Stability and control of a quadcopter despite the complete loss of one, two, or three propellers.”, IEEE International Conference on Robotics and Automation (ICRA). May 31-June 7, 2014, Hong Kong, China.

[8]. Tang, P.,J Dai, Y.; Chen,J.(2022). Non linear Robust Control on yaw motion of a variable speed unmanned aerial helicopter under multi-source disturbance .https.// doi.org/10.3390/aerospace 9010042.

[9]. Q. Xu and Y. Zhang, (2023)“Event-triggered nonlinear information fusion preview control of a two-degree-of-freedom helicopter system,” Aerospace Science and Technology, vol. 140, p. 108474, 2023.

[10]. Y. Zhang, H. Yang, Y. Chen, and W. Chen, (2022)“Adaptive extremum seeking controller via nonlinear variable gain for uncertainty model multirotor,” in 2022 41st Chinese Control Conference (CCC), 2022, pp. 2308–2314.

[11]. Zosimoveh, N(2025).A flight control system for smart tilt-rotor drone sadi international journal of science ,engineering and technology (SIJSET), 12(1),

[12]. http://doi.org/10.5281/zenodo.14779272.