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Comparative of Ziegler Nichols, Fuzzy Logic and Extremum Seeking Based Proportional Integral Derivative Controller for Quadcopter Unmanned Aerial Vehicle Stability Control

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ABSTRACT

Unmanned aerial vehicle is potentially recognized in autonomous sectors where intelligence gathering, surveillance, reconnaissance missions, power line inspection, aerial video, search and rescue monitoring devices are required. It is essential in modern era control and monitoring especially a rotary unit where quadcopter performed a crucial task. However, the flight behavior of a quadcopter is determined by the synchronous speed of each of the motors as the speed changes with load torque variations. The dynamics model equation of the system, external disturbances and its parameters variation of the motor makes it difficult for the manual tuning techniques employed into the system to perform its stability operation. The purpose of this work is to employ adaptive controllers to enhance the stability performance so as to prevent the risk of human lives and financial implication that may arise from improper monitoring of the system. Therefore, Ziegler Nichols, fuzzy logic and extremum seeking controllers were employed to auto-tuned the parameters of proportional integral derivative (PID) gains controller to optimize and give a satisfactory performance of motor speed control at different operating condition. The altitude, pitch, roll and yaw parameters of the quadcopter are simulated using the x-plane II flight simulator MATLAB tools. The simulation results presented in this work show better performance for extremum seeking-PID in terms of decrease in rise time, settling time and overshoot relative to Zigler-Nichols-PID and Fuzzy-PID controllers.

1. Introduction

Unmanned aerial vehicle (UAV) is an aircraft with no human pilot on board. It is a drone usually controlled from a ground station while some fly autonomously with no human intervention or effort. UAV is used in autonomous sectors where intelligence gathering, surveillance, reconnaissance missions, power line inspection, aerial video, search and rescue monitoring devices are required [1]. Quadcopter is a rotary wing UAV that consists of four rotors with two pairs of counter-rotating technique and a fixed-pitch blades located at the four corners of the aircraft unlike other convectional aerial vehicles that has a fixed wing. Quadcopter is the aerial vehicle that uses four rotors for lift, steering, and stabilization. It can achieve vertical flight in a more stable condition and not affected by the torque issues, which a helicopter experiences due to the main rotor [2]. Quadcopter vehicles possess certain essential characteristics, which offer a distinct advantage over other flying UAVs such as vertical take-off and landing (VTOL) as well as hovering capability, low-speed and low-altitude

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cruise as well performing aggressive maneuvers [3]. In addition, quadcopter is an under actuated dynamic vehicle with four input forces basically for propulsion and six output forces that fully coordinates the spatial movement of the vehicle, unlike the regular helicopters that have variable pitch angle rotors. Hence, a quadcopter helicopter has fixed pitch angle rotors [4].

The flight behavior of a quadcopter is determined by the synchronous speed of each of the motors, as the speed varies in opposition with load torque variations [5]. The dynamics model equation of the system, nonlinearities, external disturbances, uncertainty principle and its parameters variation of the motors makes it difficult for the manual tuning techniques employed in the UAV to perform its stability operation at different operating conditions. Therefore, an adaptive controller of Ziegler-Nichols-Proportional Integral Derivative (ZN-PID) controller, Fuzzy Logic-PID (FL-PID) controller and Extremum-Seeking-PID (ES-PID) controller was employed to maintain the quadcopter motor stability so as to prevent the risk of human lives and financial implication that may arise from improper monitoring of the system [6]. The safety and cost implication of flying quadcopter during training at a function is another problem that requires proper monitoring, optimization and control of the system flight parameters [7].

In recent years, the traditional PID controllers have been adopted for industrial automation and process control today owing to its ease of design, simplicity of operation, low cost, inexpensive maintenance, and effectiveness to a linear system. However, traditional PID controllers do not work well for non-linear systems because of its higher order in time delay and have no precise mathematical model. As a consequence, optimization artificial intelligent tuning techniques were employed such as ZN, FL and ES adaptive controllers [8]. Ziegler-Nichols and Fuzzy logic controller brings robustness and adaptive nature in constant speed variable torque drives application. It is applied to non-linear system because of their knowledge based non-linear structural characteristics. ES is an adaptive control methodology used to optimize the steady state performance of a given plant. It is a non-model method used to tune the parameters of a PID to minimize the given cost function [9]. Therefore, ZN, FL and ES are employed to auto-tune the parameters of PID gains controller of K_P, K_I, K_D to give a satisfactory performance in monitoring the dynamics altitudinal, yaw, pitch and roll angles of the UAV during hovering.

The fixed wing and rotary wing are the two classifications of UAVs. Fixed wing airplanes are comparative in design to planes in respect to cargo and human transportation. It is the constant forward development produced by the turn of a propeller that lifts these units off the ground and gives their capacity to maintain the flying [10]. Rotary wing UAVs are much similar to manned helicopters that have multiple propellers to lift the UAV and guide it in the desired direction. Rotary wing drones are excellent for tasks that require the UAV to stay still in one place or move in a limited area [11]. Quadcopter consists of four motors evenly distributed along the quadcopter frame as shown in Fig. 1.

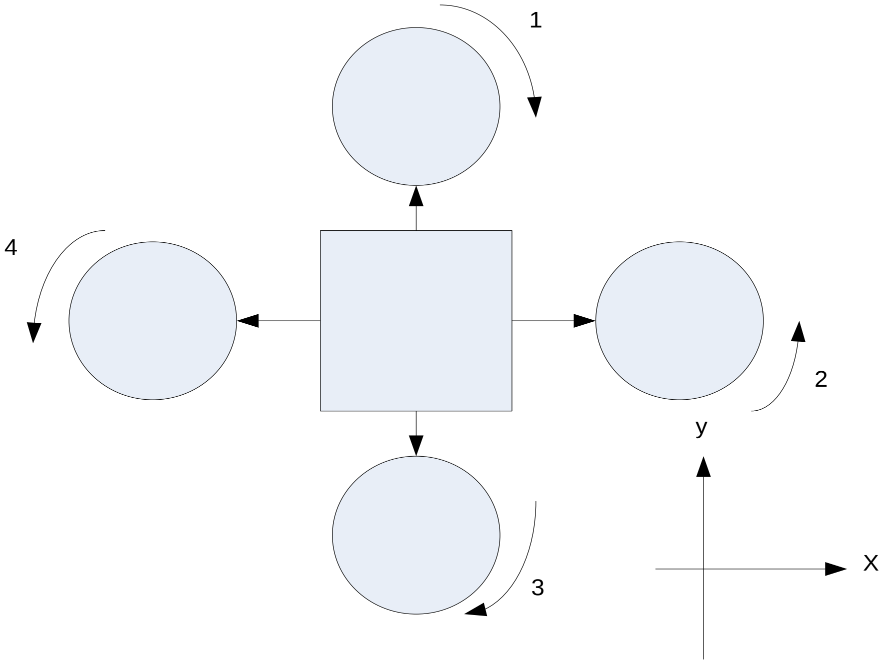

Fig. 1 Rotation direction of the quadcopter's motor [12].

The circles signify the spinning rotors of the quadcopter whereas the arrows symbolize the rotational direction. The first and third motors (i.e., motors '1' and '3') rotate in a clockwise direction using pusher rotors while motor '2' and motor '4' rotate in a counter-clockwise direction using puller rotors. Each motor produces a thrust and torque about the center of the quadcopter. Due to the opposite spinning reactions of the motors, the net torque about the center of the quadcopter is ideally zero in producing zero angular acceleration. This process eliminates the necessity for yaw stabilization. A vertical force is created by increasing the speed of all the motors by the same amount of throttle. As the vertical forces overcome the gravitational forces of the earth, the quadcopter begins to rise in altitude [12].

Jose et al. [13] worked on a pole placement method to tune PID controller for controlling and stabilization of quad rotor structure. The authors used the technique to control the rotational speed of the four motors independently. The simulation results were validated with experimental measurement in prototype quad rotor. The approach requires additional research because the controller does not meet the requirements when the velocities of all motors are simultaneously increased due to nonlinearity present in the system.

Muller et al. [14] proposed an adaptive PID controller for fault-tolerant control of a quad rotor helicopter system in the presence of actuator faults. The authors used tracking errors as well as the changes in tracking errors in the fuzzy scheduler to make the system act faster and more effectively in the event of fault occurrence. The results showed the effectiveness of the applied technique and its ability to adapt in the presence of uncertainties and external disturbances.

Arbab et al. [15] proposed a method for controlling small unmanned helicopter under light air turbulent environment. An intelligent FL controller was used because of its distinct qualities for position control, height and attitude. Fuzzy logic control effectively attained hovering under mild and ideal turbulent weather conditions, but the controller was not able to completely handle sensor created noise and contradictory inputs normally encountered in flight control.

Bittar et al. [16] proposed a technique to simulate a guidance algorithm running on Simulink package to control a fixed wing unmanned aircraft model running on x-plane flight simulator. A guidance algorithm based on way points was used to confirm the software-in-the-loop where the UAV needs to complete two missions. The method was limited to a customized small unmanned aerial vehicle.

Diego et al. [17] proposed a PID controller applied to an UAV. A model for the yaw movement of a miniature coaxial helicopter with the identification of the yaw movement was proposed to achieve autonomous flight conditions suitable for surveillance in narrow spaces. Yaw movement was chosen because it is weakly coupled with other degree of freedom and it is safer to put an identification signal on the rudder input than on aileron and elevator. A single-input single-output configuration was proposed based on a simplified model, which enables control on one of three axes, the z-axis (yaw). The frequency response for the yaw movement was obtained using comprehensive identification frequency responses (CIFR) and classical transfer function analyzer (CTFA). The simulation results were validated with experimental data collected from the UAV during flight. The real-life tests with the controller show that the helicopter has increased stability, allowing for a safer identification of the other movements.

Santos et al. [18] presented an algorithm to accomplish quadcopter trajectory tracking tasks by controlling the altitude using an adaptive dynamic controller that was capable of dealing with uncertainties in model parameters. Jayakrishnan [19] and Xiong et al. [20] used the sliding mode control (SMC) technique to control the horizontal position and attitude while also providing a significant improvement of altitude control. Also, another method was presented by Muliadi et al. [21], where the authors proposed a neural network approach to control UAV altitude dynamics. The results obtained with this method were verified through comparisons with a conventional PID control system. However, these approaches have a common disadvantage in which the SMC technique generates a high chattering control signal method, which reduces the lifetime of the entire system.

Most of the recent work in the literature only lay emphasizes on the convectional controller, but no account was reported on the use of hybridized adaptive controllers' approach to control the motor speed simultaneously. Therefore, this paper presents a hybridized optimal controller to overcome the non-linearity problem, torque ripple, minimized the overshoot percentages. The significance of this study is to enhance the stability control of quadcopter UAV using adaptive controllers to prevent the risk of human lives and financial implication that may arise from improper monitoring of the system.

2. Modeling Approach of the Quadcopter Stability Control

The stability control of quadcopter in terms of the altitude, pitch, yaw and roll control is presented in Fig. 2. The rotational speed of the quadcopter in revolution per minute was determined by the adjustment of the applied voltage in order to reach the desired speed. The altitude, pitch, roll and yaw parameters of the quadcopter were deduced from x-plane II flight simulator tools after establishing a serial communication connection between x-plane in MATLAB packages. The flight simulator was used to generate the flight data for the dynamic's quadcopter. The environmental setting menu of the x-plane, the date and time in x-plane were first set by in moving the cursor to the top of the screen and clicking on "Environment and Selecting Date and Time". The weather parameters such as cloud coverage intensity and temperature were adjusted to a highly plausible weather condition as shown in Fig. 3.

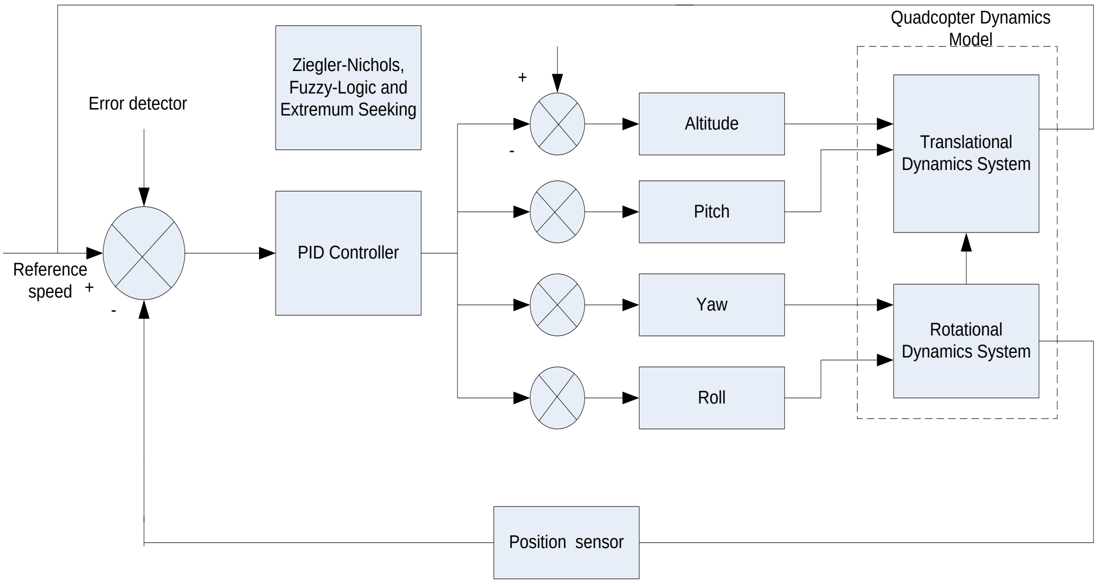

Fig. 2 Model for Complete Quadcopter Control using the Artificial Intelligent Controller.

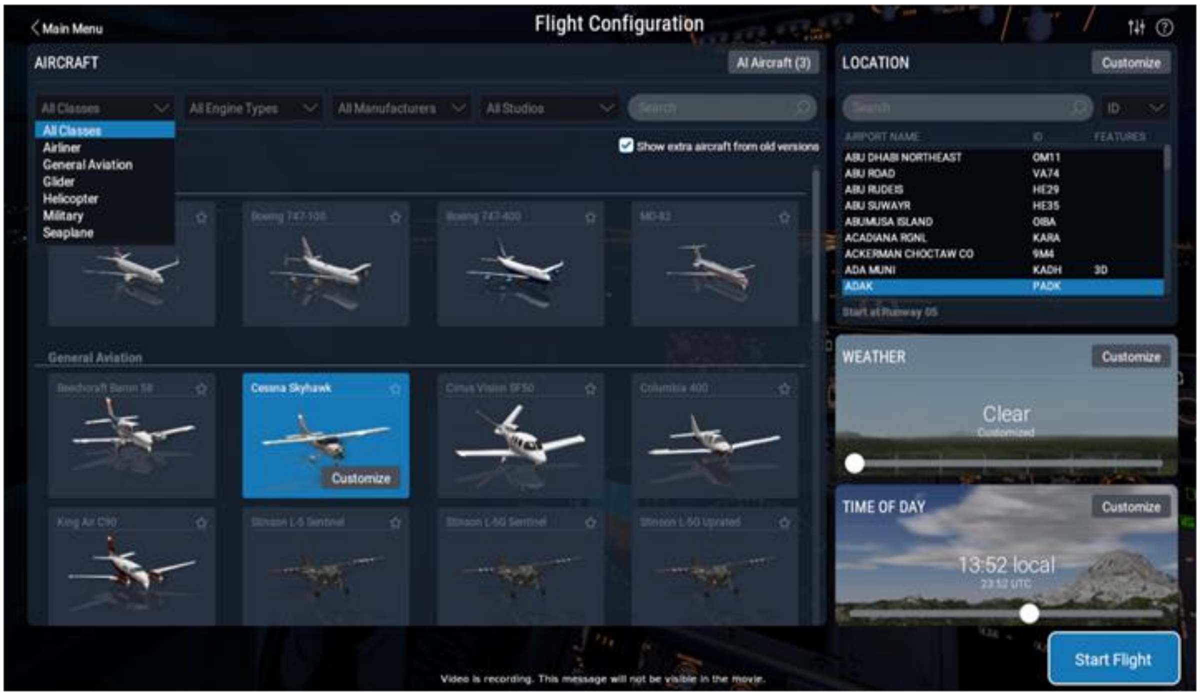

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Fig. 3 GUI for Flight Selection and Environmental Settings.

3. Mathematical Modeling for Quadcopter Control

The fundamental mechanics parameters that were used to determine the dynamics stability of quadcopter tuned PID controller are expressed in this section. The quadcopter has four propellers as shown in Fig. 4. These serve as input forces to generate thrust responsible for its motion. Considering the center of gravity of the quadcopter to be the middle of the mass, as it increases up or down, the angular acceleration becomes less sensitive to the forces acting on it, as a result of this, the quadcopter stability increased.

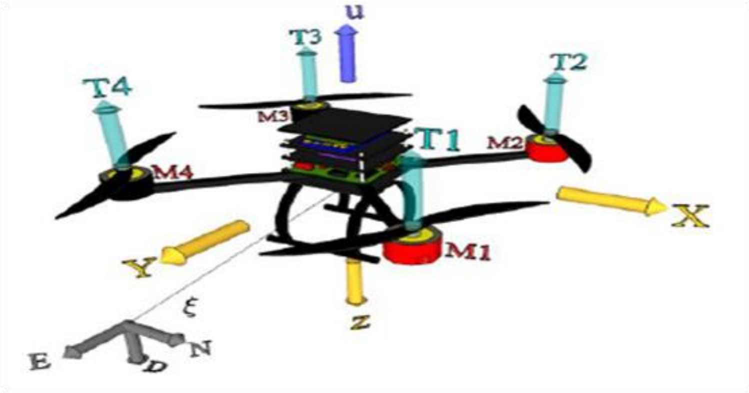

Fig. 4 Inertial and Body Frame of Quadcopter.

3.1. Altitude Control

The thrust force control variable, U_1 is defined as:

$$U_1 = K_{PZ}e_Z + K_{IZ}\int e_Z - K_{DZ}\frac{d}{dt}e_Z \tag{1}$$

$$e_Z = Z_{des} - Z_{mes} \tag{2}$$

Where, K_{PZ}, K_{IZ} and K_{DZ} are three altitude PID controller parameters, e_z is the altitude error, Z_{des} is desired altitude and Z_{mes} is the measured altitude.

3.2. Roll Control

The roll moment control variable, U_2 is expressed as:

$$U_2 = K_{P\varphi}e_\varphi + K_{I\varphi}\int e_\varphi - K_{D\varphi}\frac{d}{dt}e_\varphi \tag{3}$$

$$e_\varphi = \varphi_{des} - \varphi_{mes} \tag{4}$$

Where, $K_{P\varphi}$, $K_{I\varphi}$ and $K_{D\varphi}$ are three roll angle PID controller parameters, e_φ is the roll angle error, φ_{des} is the desired roll angle and φ_{mes} is the measured roll angle.

3.3. Pitch Control

The pitch moment control variable, U_3 is stated as:

$$U_3 = K_{P\theta}e_\theta + K_{I\theta}\int e_\theta - K_{D\theta}\frac{d}{dt}e_\theta \tag{5}$$

$$e_\theta = \theta_{des} - \theta_{mes} \tag{6}$$

Where, $K_{P\theta}$, $K_{I\theta}$ and $K_{D\theta}$ are three pitch angle PID controller parameters, e_θ is the roll angle error, θ_{des} is the desired pitch angle and θ_{mes} is the measured pitch angle.

3.4. Yaw Control

The equation for the yaw moment control variable U_4 is:

$$U_4 = K_{P\psi}e_\psi + K_{I\psi}\int e_\psi - K_{D\psi}\frac{d}{dt}e_\psi \tag{7}$$

$$e_\psi = \psi_{des} - \psi_{mes} \tag{8}$$

Where, $K_{P\psi}$, $K_{I\psi}$ and $K_{D\psi}$ are three yaw angle PID controller parameters, e_ψ is the yaw angle error, ψ_{des} is the desired yaw angle and ψ_{mes} is the measured.

The inputs are defined as follow:

$$\begin{aligned} U_1 &= \quad (Th_1 + Th_2 + Th_3 + Th_4)/m \\ U_2 &= l(-Th_1 - Th_2 + Th_3 + Th_4)/I_1 \\ U_3 &= l(-Th_1 + Th_2 + Th_3 - Th_4)/I_2 \\ U_4 &= C(Th_1 + Th_2 + Th_3 + Th_4)/I_3 \end{aligned} \tag{9}$$

Where, $Th_i's$ are the thrusts generated by the four rotors and are considered as the real control inputs to the system; C is the force to moment scaling factor; I_i'sare the moment of inertia with respect to the axes; l is the half length of the quadcopter and m is the total mass of the quadcopter. Each of the inputs is to control certain side of the quadcopter model; U_2 control the rotation in the roll angle; U_3 will control the pitch angle; U_4 is to control the yaw angle during the flying process and U_1 will control the altitude (z-axis) for this model.

The orientation of the body frame axes with respect to the earth frame axes was accomplished with four Euler angles such as altitude angle $\emptyset$, roll angle ϕ, pitch angle θ and yaw angle ψ. The four Euler angles form of vector is given as:

$$\Omega^T = (\varphi, \phi, \theta, \psi) \tag{10}$$

The absolute linear position of the quadcopter in the inertial frame is given by the vector as:

$$\xi^T = (x, y, z) \tag{11}$$

In the body frame, the force required for the acceleration of mass $m\dot{V}_B$ and the centrifugal force $\nu \times (mV_B)$ are equal to the gravity $R^T G$ and the total thrust of the rotors T_B. Thus,

$$m\dot{V}_B + \nu \times (mV_B) = R^T G + T_B \tag{12}$$

In the inertial frame, the centrifugal force is nullified. Thus, only the gravitational force and the magnitude and direction of the thrust contributed in the acceleration of the quadcopter. In linear analysis, the translational dynamic model is expressed as:

$$\begin{bmatrix} I_{uu}\dot{\varphi} \\ I_{xx}\ddot{\phi} \\ I_{yy}\ddot{\theta} \\ I_{zz}\ddot{\psi} \end{bmatrix}_{r,i} + \begin{bmatrix} \varphi(I_{uu} - I_{xx}) \\ \dot{\psi}(I_{uu} - I_{yy}) \\ \dot{\theta}(I_{yy} - I_{zz}) \\ \dot{\phi}(I_{yy} - I_{xx}) \end{bmatrix}_{r,i} = \begin{bmatrix} \tau_\varphi \\ \tau_\phi \\ \tau_\theta \\ \tau_\psi \end{bmatrix}_r \tag{13}$$

Where, $\tau = [\tau_\varphi, \tau_\phi, \tau_\theta, \tau_\psi]$, is the external force and torque vectors applied on the quadcopter center of gravity. The τ_φ,τ_ϕ, τ_θ and $\tau_\psi$are the altitude, roll, pitch and yaw torques respectively. The rotational dynamic models of quadcopter are shown respectively.

$$\begin{aligned} \varphi &= \dot{\theta}\dot{\psi} \left(\frac{I_{xx}-I_{zz}}{I_{yy}}\right) - \frac{\omega J_r}{I_{xx}} + \frac{lk\,(\omega_1^2-\omega_2^2)}{I_{zz}} \\ &= \dot{\theta}\dot{\psi} \left(\frac{I_{xx}-I_{zz}}{I_{yy}}\right) - \frac{\omega J_r}{I_{xx}} + \frac{l}{I_{zz}}\, u_2 \end{aligned} \tag{14}$$

$$\begin{aligned} \ddot{\phi} &= \dot{\theta}\dot{\psi} \left(\frac{I_{yy} - I_{zz}}{I_{xx}}\right) - \frac{\dot{\theta}\omega J_r}{I_{xx}} + \frac{lk\,(\omega_4^2 - \omega_2^2)}{I_{xx}} \\ &= \dot{\theta}\dot{\psi} \left(\frac{I_{yy}-I_{zz}}{I_{xx}}\right) - \frac{\dot{\theta}\omega J_r}{I_{xx}} + \frac{l}{I_{xx}}\, u_2 \end{aligned} \tag{15}$$

$$\begin{aligned} \ddot{\theta} &= \dot{\phi}\dot{\psi}\left(\frac{I_{zz} - I_{xx}}{I_{yy}}\right) + \frac{\dot{\phi}\omega J_r}{I_{yy}} + \frac{lk\,(\omega_3^2 - \omega_1^2)}{I_{yy}} \\ &= \dot{\phi}\dot{\psi}\left(\frac{I_{zz}-I_{xx}}{I_{yy}}\right) + \frac{\dot{\phi}\omega J_r}{I_{yy}} + \frac{l}{I_{yy}}\, u_3 \end{aligned} \tag{16}$$

$$\begin{aligned} \ddot{\psi} &= \dot{\phi}\dot{\theta}\left(\frac{I_{xx} - I_{yy}}{I_{zz}}\right) - \frac{\dot{\omega} J_r}{I_{zz}} + \frac{\sum_{i=1}^{4}\left[(-1)^i b\omega_i^2\right]}{I_{zz}} \\ &= \dot{\phi}\dot{\theta}\left(\frac{I_{xx}-I_{yy}}{I_{zz}}\right) - \frac{\dot{\omega} J_r}{I_{zz}} + \frac{b}{I_{zz}} u_4 \end{aligned} \tag{17}$$

4. Results and Discussion

The aerodynamic data-based altitude, yaw, roll, and pitch is essential for quadcopter stability using adaptive controllers of ZN-PID, FL-PID and ES-PID. The comparison performance of ES-PID, ZN-PID and FL-PID controller for quadcopter altitude control in respect to the time taken is as shown in Fig. 5. The ES, ZN and FL method was used to tune the PID parameters. The rise time, settling time and overshoot percentage are 0.89 s, 1.25 s, 1.89 s; 0.18 s, 0.93 s, 1.28 s; and 0.01 %, 0.02 %, 0.04 % respectively. There is no presence of distortion along the settling path within the specified band of 20 % up to 60 % of the steady value. Therefore, the result indicates no presence of steady state error.

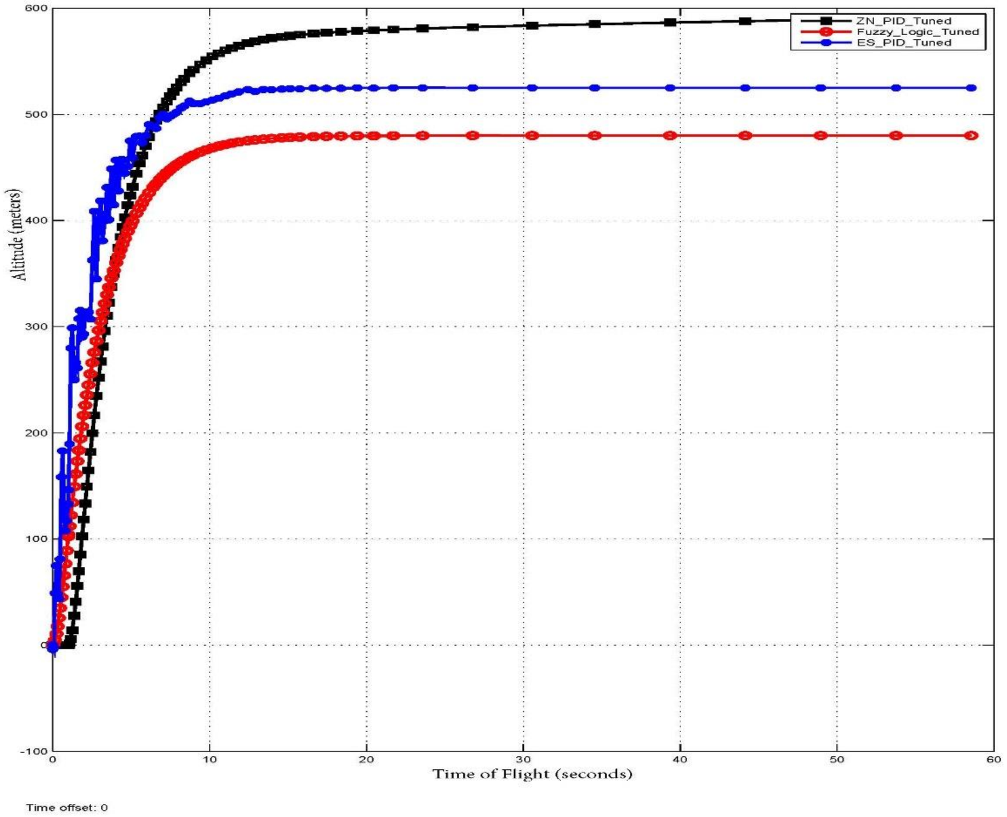

Fig. 5 Comparison of ES-PID, ZN-PID and FL-PID Controllers Quadcopter Altitude.

The comparison performance of ES-PID, ZN-PID and Fuzzy-PID controller for quadcopter pitch control using x-plane II with time taken is as shown in Fig. 6. The ES, ZN and FL method was used to tune the PID parameters. The rise time, settling time and overshoot percentage are 1.12 s, 1.83 s, 2.23 s; 1.18 s, 1.96 s, 2.25 s; and 0.02 %, 0.04 %, 0.06 %, respectively. The result indicates the presence of steady state error due to the presence of distortion along the settling path.

The comparison performance of ES-PID, ZN-PID and FL-PID controller for quadcopter roll control using x-plane II with time taken is as shown in Fig. 7. The ES, ZN and FL method was used to tune the PID parameters. The rise time, settling time and overshoot percentage were 1.15s, 1.18s, 2.25s; 1.22s, 2.58s, 3.35s and 0.02%, 0.05%, 0.07% respectively. The result indicates the presence of steady state error due to the presence of distortion along the settling path.

The comparison performance of ES-PID, ZN-PID and FL-PID controller for quadcopter Yaw control using x-plane 11 with time taken is as shown in Fig. 8. The ES, ZN and FL method was used to tune the PID parameters. The rise time, settling time and overshoot percentage were 1.17s, 2.25s, 4.20s; 1.28s, 2.88s, 3.98s and 0.04%, 0.07%, 0.09% respectively. The result indicates the presence of steady state error due to the presence of distortion along the settling path.

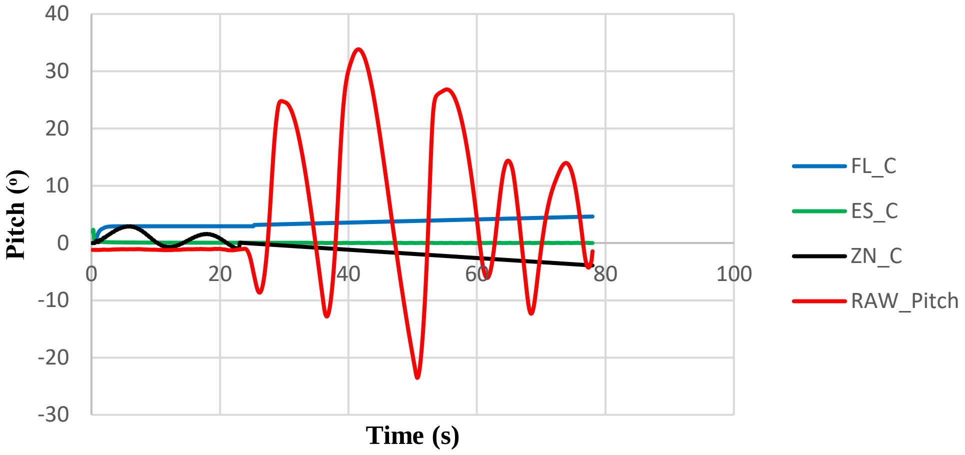

Fig. 6 Comparison of ES-PID, ZN-PID and FL-PID Controllers Quadcopter for Raw_Pitch.

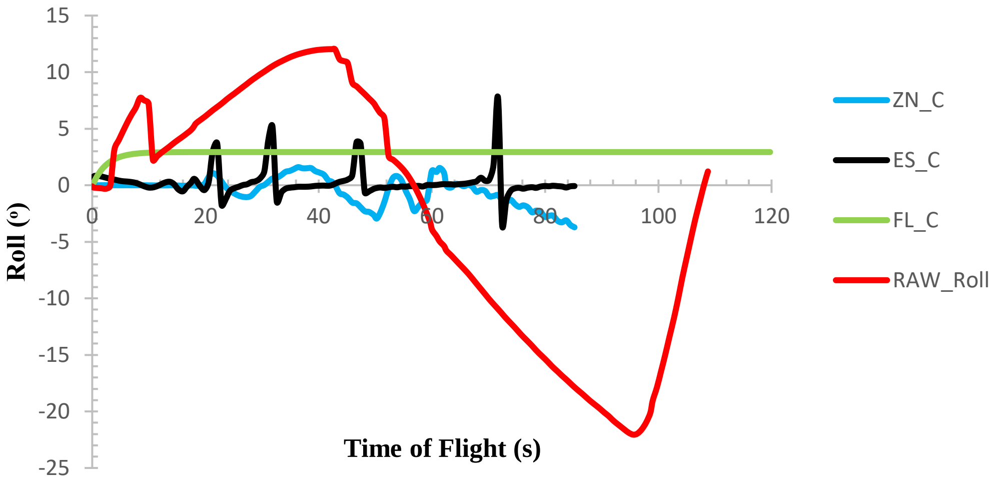

Fig. 7 Comparison of ES-PID, ZN-PID and FL-PID Controllers Quadcopter Raw_Roll.

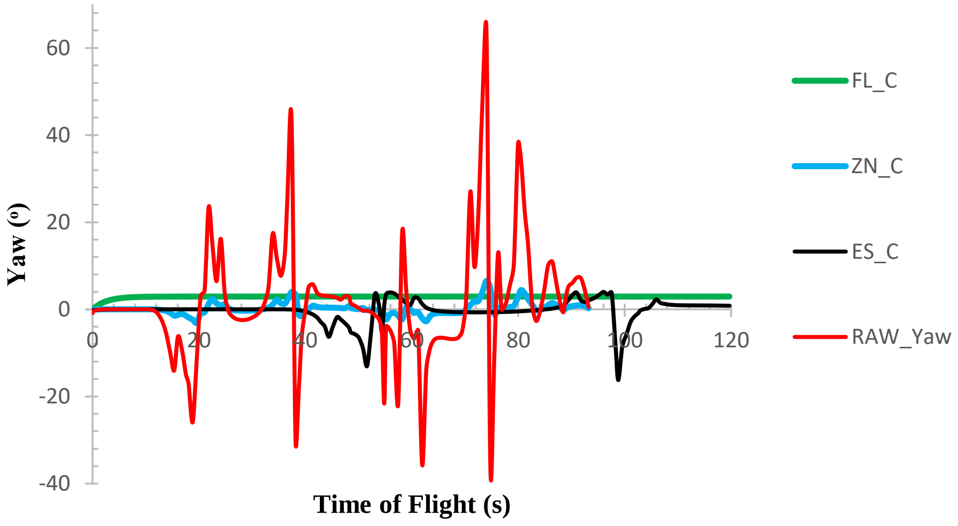

Fig. 8 Comparisons of ES-PID, ZN-PID and FL-PID Controllers Quadcopter Raw_Yaw

5. Conclusion

This work has provided a solution to solve the problem of quadcopter motor speed on load torque variation at different operating conditions using adaptive controllers. The observe simulation results showed the comparison of quadcopter Altitude, Pitch, Roll and Yaw in terms of the rise time, settling time and percentage overshoot for ES-PID, FL-PID and ZN-PID controller. The performance evaluation was deduced that ES-PID controller gave a better control performance in terms of decreases in rise time of 0.89 s, 1.12 s, 1.15 s, 1.17 s; settling time of 0.18 s, 1.18 s, 1.22 s, 1.28 s and percentage overshoot of 0.01 %, 0.02 %, 0.02 % and 0.09 % in relative to other standard tuning controller presently in use. Hence, the developed techniques can be effectively deployed to aerial images, monitoring, industrial inspection and maintenances for aircraft sectors. Future work will tend to focus on Nero-fuzzy approaches which may learn rule base and identify the membership function parameters more accurately so as to enable it to deliver more effectively and eliminate the steady state errors.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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