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# Design of Self-tuning PID Controller Parameters Using Fuzzy Logic Controller for Quad-rotor Helicopter

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***Abstract--*** This paper presents the design of a Fuzzy PID controller (FPID) based on fuzzy logic with a PID structure with many valued logic and reasoning. The self-turning Fuzzy PID control take in an error and the rate of change of error of the altitude and attitude of the quadrotor as the input to the fuzzy controller and use the fuzzy rules to adjust the PID parameter automatically. Simulations have been conducted to observe the differences in controlling the quadrotor in flight using the new FPID controller instead of using PID controller. The effectiveness of the developed FPID is verified using the dSPACE platform whereby the Simulink model of the controller is converted to a real time system to generate the control signals for the control of quad rotor helicopter.

***Index Terms--*** *PID control, Fuzzy logic control and Fuzzy-PID control, dSPACE, MatLab/Simulink.*

## I. INTRODUCTION

A quadcopter, also known as a quadrotor, is a multirotor helicopter that generates lift and propulsion using four rotors. Quadrotor are classified as rotorcraft, as opposed to fixed-wing aircraft, because their lift is generated by a set of vertically oriented propellers. Early in the history of flight, multirotor aircraft were explored in order to circumvent traditional stabilization problems of rotorcraft. Configurations such as the helicopter have inherent control problems due to the torque generated by the large main rotor. In a helicopter, this problem is combated by a small vertical tail rotor that aims to prevent the main body of the rotorcraft from rotating. Beyond complicating the system, the use of a tail rotor has a downside in that it requires additional motors that do not contribute to lift. Because weight reduction and efficiency are vital in flying mechanisms, additional motors are often unsustainable or undesirable. As a result, multirotor designs emerged, using opposite rotor pairs to cancel out unwanted rotational energy while still providing lift. Additionally, by using four rotors to generate lift, each rotor can be much smaller in diameter. This reduces the amount of kinetic energy present in each rotor, reducing the force of impact in the case of a crash. Due to these various advantages, a number of manned designs appeared in the 1920s and 1930s. These vehicles were some of the first successful heavier-than-air vertical take-off and landing (VTOL) vehicles. The main fall-backs to these pioneering designs were poor performance and too much pilot workload, the latter induced by primitive control systems. Recently, quadcopter designs have become popular in the field of unmanned aerial vehicle research. Generally small in size, quadcopters use a variety of sensors to achieve a high level of stability and control, allowing them to navigate even in narrow spaces. Additionally, because each rotor is small, they require less power during flight, which makes quadcopters much safer both to human operators and to the flight environment. Lastly, quadcopters are generally low cost and easy to construct. All these factors contribute to making them the rotorcraft of choice for most academic and research purposes.

In recent years, Unmanned Aerial Vehicles (UAVs) have attracted more attention due to their high manoeuvrability, simplicity of construction, low maintenance costs and low noise. However, a quad-rotor has six degree of freedom (6-DoF) of flight control system which exhibits a high degree of nonlinear dynamic analytical representations.

Design of control system for quadrotor helicopters is an ongoing and growing research field. The controller is the main part in designing any autopilot system for aviation and quadrotor helicopter in particular [1]. For a stable control, the throttle, roll, pitch and yaw have to be controlled successfully so that the vehicle navigate its terrain while maintaining steady, stable flight and controlled movement.

The goal of this paper is to a design a Fuzzy PID controller (FPID) based on fuzzy logic with a PID structure with many valued logic and reasoning. The self-turning Fuzzy PID control take in an error and the rate of change of error of the altitude and attitude of the quadrotor as the input to the fuzzy controller and use the fuzzy rules to adjust the PID parameter automatically. Simulations have been conducted to observe the differences in controlling the quadrotor in flight using the new FPID controller instead of using PID controller [2].

This paper will present a FPID controller for a quadrotor helicopter development simulation using Matlab/Simulink software. The developed model will be used to investigate the dynamics response of the system. Furthermore, the non-linear strategies are used to control the quadrotor with the aim of easy implementation of feedback system which gives a unique construction of non-linear controllers using Fuzzy-PID. The dynamics of quadrotor are developed using mathematical models formulated using the Newton-Euler. The formulation is based on the control laws used to design and stabilize the craft at hovering position. The PID controller is chosen as a benchmark control algorithm, where it is used for comparison of performance. The dSPACE platform is used to corroborate or otherwise the design and development of the FPID for quadrotor applications.

## II. ANALYTICAL DYNAMIC MODELLING

In order to design a valid control scheme for a system, a representative model is needed. An often used approach in relation to modelling physical systems is to divide them into subsystems and to define the inputs and outputs relationships of the subsystems using the laws of physics. The model should prevail from assumptions such as empirical modelling and fitting of the model parameters. This approach is often referred to as the First Principles model as it is based exclusively on the laws of physics.

The first step before the control stage, is the adequately model the dynamics of the quad rotor system. This phase provides an insight into the controllability of the aircraft a better understanding of the overall system capabilities and limitations.

Any mathematical model is simply an approximation of the real world, describing any relevant influences of input signal on the output of the system. In this paper the model describes how the quadrotor moves in a 6 dimensional space depending on the four control commands, namely throttle, Roll, Pitch and Yaw.

To define a position in a space, a coordinate frame (system) should be defined. A coordinate frame is usually defined by two set points namely its origin (specified in space) and its orientation. For the quad rotor, the first frame of reference is the earth inertial frame (EIF) where it is considered to be stationary or moves with constant velocity. The second frame is represented by the quadrotor body fixed frame (BFF) which moves at the same a velocity but opposite direction as shown in fig. 1(a). The latter coordinate frame represents a rotating frame which follows the classical mechanics of Newton's law for angular motion.

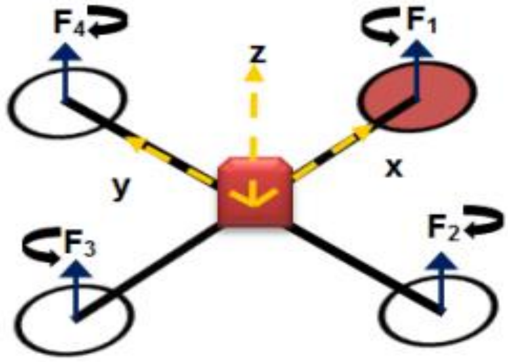


Figure 1: Inertial and Body Fixed Frame

The orientations of both frames is a North, East and Down convention which is a standard of aviation and both follow the right hand rule. Euler Angles (φ, θ, ψ) are used to describe the orientation of the rotating body fixed frame with respect to the inertial frame.

### *A. Quad-rotor Analytical Dynamic Model*

The dynamic behavior of the quad-rotor is usually described by a nonlinear dynamic model, which consists of differential equations, shown by the set of equation (1). Such equations are implemented using block libraries in Matlab/Simulink software. The equations can be linearized using the first order

Taylor series and the Laplace transform transfer function can be used to simplify the method of solution to reduce computation time [3,4]

$$\begin{bmatrix} V \\ \ddot{\varphi} \\ \ddot{\theta} \\ \ddot{\psi} \\ \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = \begin{bmatrix} \frac{RD\Omega^2}{k_q} + \frac{RJ\dot{\Omega}}{k_q} + k_e\Omega \\ \frac{2\rho Al}{I_{xx}}\left[\frac{f\eta k_t}{k_q}\right]^2 (V_2{}^2 - V_4{}^2) \\ \frac{2\rho Al}{I_{yy}}\left[\frac{f\eta k_t}{k_q}\right]^2 (V_3{}^2 - V_1{}^2) \\ \frac{J}{I_{zz}}(\dot{\Omega}1 + \dot{\Omega}3 - \dot{\Omega}2 - \dot{\Omega}4) + \frac{D}{I_{zz}}(\Omega_1{}^2 + \Omega_3{}^2 - \Omega_2{}^2 - \Omega_4{}^2) \\ \frac{2\rho A}{m}\left[\frac{f\eta k_t}{k_q}\right]^2 \left(V_1{}^2 + V_2{}^2 + V_3{}^2 + V_4{}^2\right)(\cos\varphi \sin\theta \cos\psi + \sin\varphi \sin\psi) \\ \frac{2\rho A}{m}\left[\frac{f\eta k_t}{k_q}\right]^2 \left(V_1{}^2 + V_2{}^2 + V_3{}^2 + V_4{}^2\right)(\sin\varphi \sin\theta \cos\psi - \cos\varphi \sin\psi) \\ \frac{2\rho A}{m}\left[\frac{f\eta k_t}{k_q}\right]^2 \left(V_1{}^2 + V_2{}^2 + V_3{}^2 + V_4{}^2\right)(\cos\theta \cos\varphi) - g \end{bmatrix}$$

### *B. Simulink Model of the Quadrotor Analytical Dynamic Model*

The model of the whole system is composed of several interconnected blocks, fig 1(b). The dynamics represent the physics of the quad-rotor and provide the displacements, velocities and accelerations of both linear and angular quantities. The inputs, labelled $V_1$, $V_2$, $V_3$ and $V_4$ are the voltages, which serve as motor control inputs for the brushless DC motors. The outputs can be selected at will from the variables available, some of which are $x, y, z, u, v, w, \varphi, \theta, \psi, p, q, r$ .

The outputs of the actuator sub-systems are the angular velocities of the propellers (rad/s). These serve as inputs to the yaw subsystem, which computes the yaw angular acceleration. The other subsystems labelled roll, pitch, x-motion, y-motion and z-motion are also fed with the same motor control inputs.

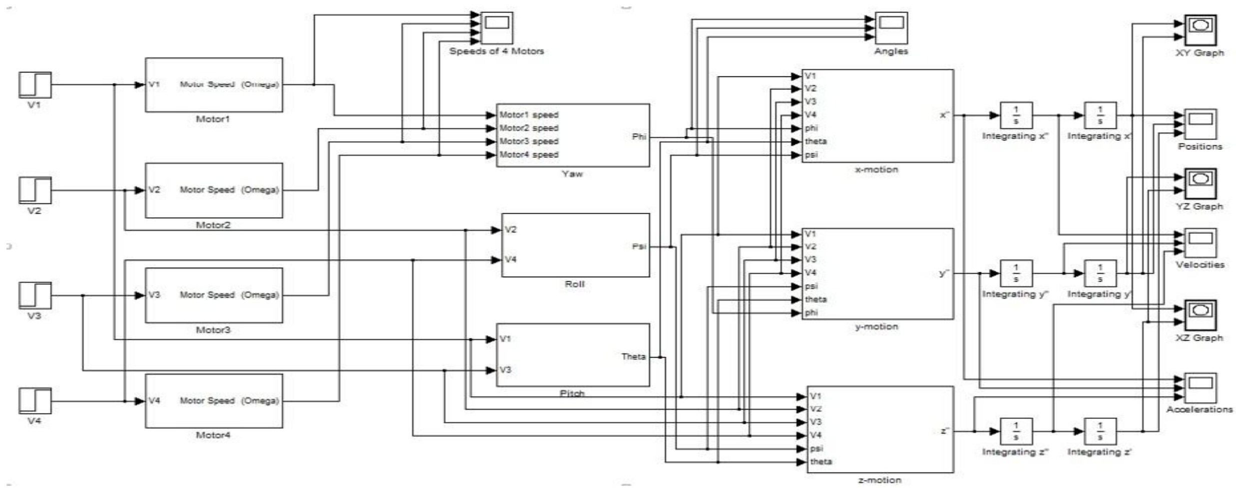


**Fig. 1(b). Simulink model of the quadrotor dynamic model**

## III. THE FUZZY PID CONTROLLER

A Fuzzy PID controller is a controller that is based on Fuzzy logic with a PID structure [3]. The fuzzy logic controller deals with many-valued logic and reasoning instead of fixed and exact values which has the truth level varying from 0 to 1 instead of being fixed as either 0 or 1 [4]. This is very helpful in controlling the systems especially if the exact model of the system is not available. A typical structure for a Fuzzy logic controller is to have two inputs, the first input is the error *e(k)* and the second input is the rate of change of the error *é(k)*. To make the fuzzy logic controller function as a PID controller the following structure, fig. 3, is adopted. After designing the structure of the Fuzzy PID controller a set of membership functions has to be designed and tuned to control the system, and the associated set of rules are generated to govern the membership functions of the input/ output relationship.

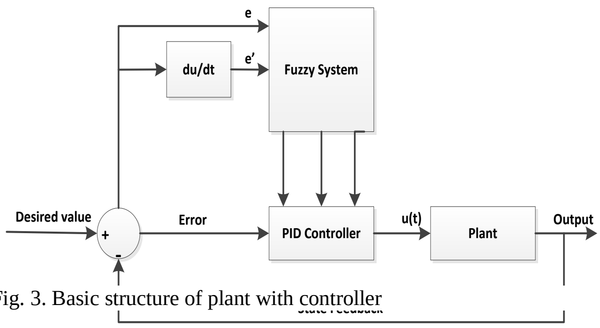


Fig. 3. Basic structure of plant with controller

### *A. The Self-Tuning of Fuzzy PID Controller*

Table1: Fuzzy Logic Rules for $K_p$ and $K_i$

| | | ERROR | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ERROR RATE | | NB | NM | NS | ZO | PS | PM | PB |
| | NB | M | S | VS | VVS | VS | S | M |
| | NM | B | M | S | VS | S | M | B |
| | NS | VB | B | M | S | M | B | VB |
| | ZO | VVB | VB | B | M | B | VB | VVB |
| | PS | VB | B | M | S | M | B | VB |
| | PB | B | M | S | VS | S | M | B |
| | PM | M | S | VS | VVS | VS | S | M |

The self-turning fuzzy PID control take in an error and the rate of change of error of the altitude and attitude of the quadrotor as the input to the fuzzy controller and use the fuzzy rules to adjust the PID parameter automatically. The variation in $\Delta K_P$, $\Delta K_I$ and $\Delta K_D$ of PID control parameters $K_P$, $K_I$ and $K_D$ are the output variables of the fuzzy logic. The quadrotor angle and position deviation *e* and its gradient *de* are sampled and calculated in real time, the output variables $\Delta K_P$, $\Delta K_I$ and $\Delta K_D$ are extracted from the fuzzy matrix table based on the fuzzy rules and reasoning. The PID control parameters are adjusted using $\Delta K_P$, $\Delta K_I$ and $\Delta K_D$ in order to realize the real-time dynamic control of the quadrotor angle and displacement.

### *B. The Design of Self-Tuning of Fuzzy PID Controller for throttle*

For the quadrotor position control requirement, the domain of the displacement deviation *e* is set as [-1 1], and the domain of the *de* is [−10 10]. The domains of $\Delta K_P$, $\Delta K_I$ and $\Delta K_D$ for PID parameters are [0.4 0.8], [0.002 0.02] and [0.15 0.2] respectively. *Fuzzy Logic Rules*, the triangle and Gaussian membership function are adopted. The fuzzy logic rules are deduced, as listed in Table I. In this table, NB, NM, NS, ZO, PS, PM, PB represent negative big, negative medium, negative small, zero, positive small, positive medium, and positive big, respectively and the output with seven fuzzy value VVS, VS, S, M, B, VB, VVB represent Very Very Small, Very Small, Small, Medium, Big, Very Big and VVB Very Very Big respectively. As it can be seen from the block diagram, the fuzzy system takes two inputs (*e* and *de*) and gives three outputs $K_p$, $K_i$ and $K_d$, fig. 4. fig. 5 shows the 3D variation of Kp as a function of *e* and *de*, fig. 6 the general FPID controller used for the throttle, Roll and Pitch, and fig. 7 shows the overall non linearized dynamic quadrotor Simulink model.

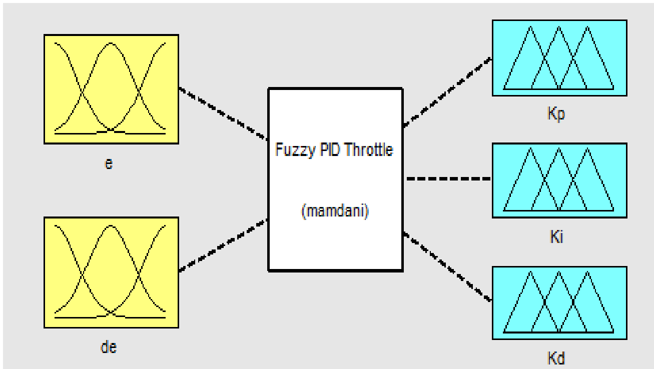


Figure 4: Basic structure of a fuzzy-PID controller for throttle

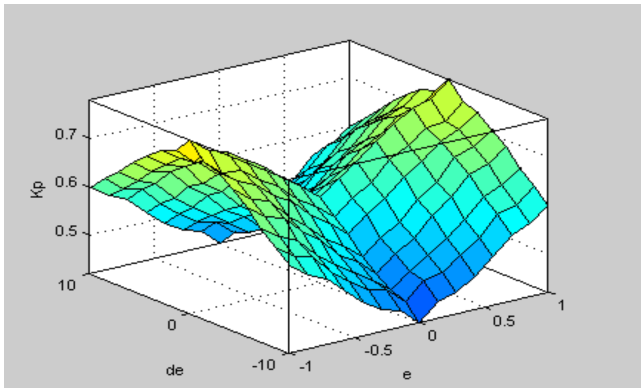


Figure 5: The error and derivative error for the output Kp.

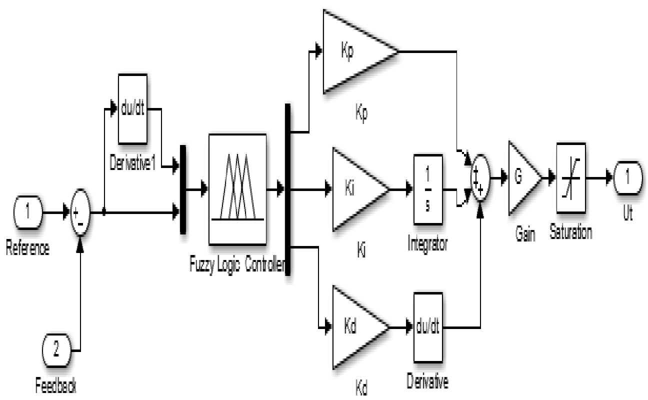


Figure 6: General controller for Throttle, Roll and Pitch

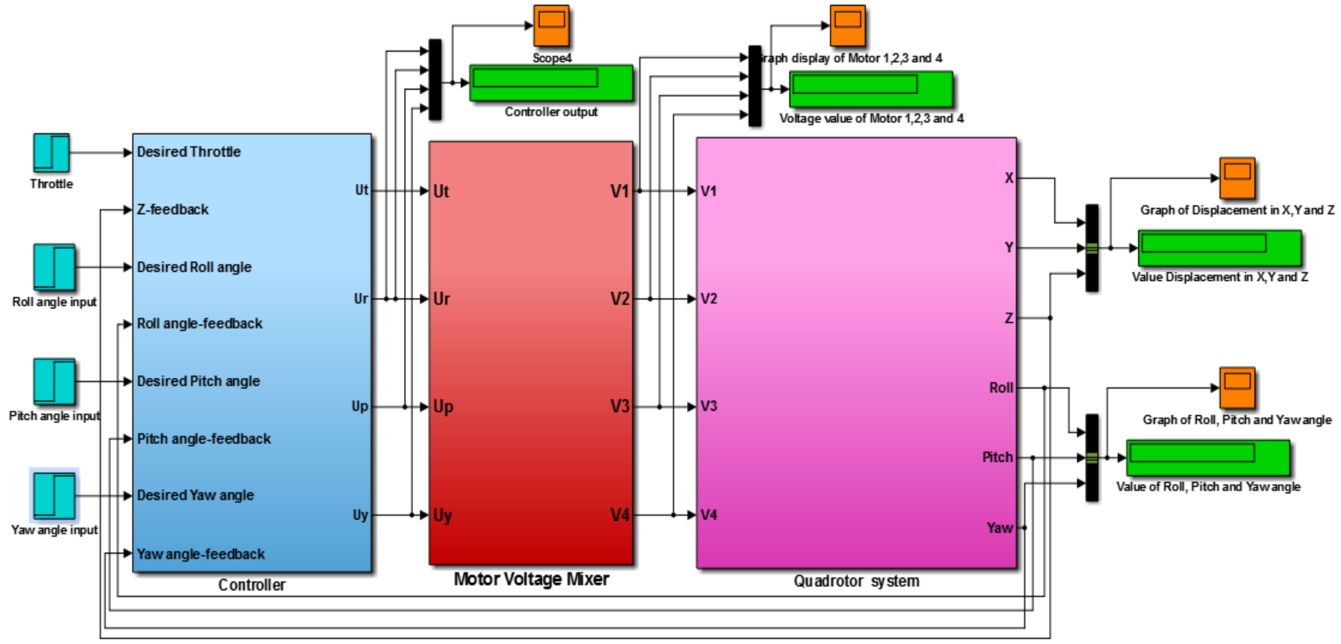


Figure 7: The complete non-linearized dynamic quadrotor Simulink model

## IV. SIMULATION AND RESULT FOR PID CO4NTROLLER DESIGN

The rules presented at Table I can be read as follows; for example, IF the error is NB and the error rate is PS THEN $K_p$ is VB and $K_i$ is VB and $K_d$ is VS [3]. The output of the fuzzy system logic is fuzzy. Therefore it is necessary to use the defuzzyfication process to convert Fuzzy outputs to numbers before they are fed to the dynamic model. The defuzzification algorithm should provide continuous control (output) signals and correspond to approximately to the centre average.

Fig. 8 shows the throttle response of the system for the PID and FPID, figs. 9 and 10 show the Roll responses for the PID and FPID respectively and figs. 11 and 12 show the Pitch responses respectively.

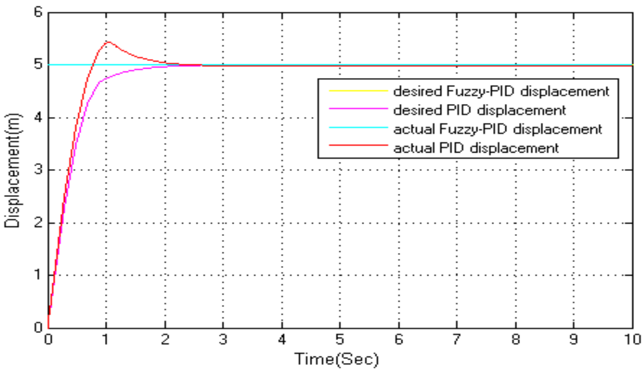


Figure 8: Throttle response for the PID and FPID

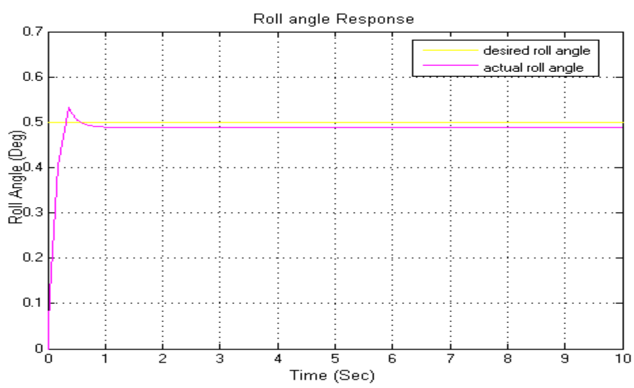


Figure 9: Roll angle PID design response

The initial state of the quadrotor position and angles are as follows; $Z_0$= 5m; $\phi_0$= $\theta_0$= 0.8 degree (For Classical PID $\phi_0$= $\theta_0$= 0.5 degrees) and $\psi_0$=0 degrees.

For the PID controller, the gain values for the four independent PID controllers were tuned independently using the manual turning technique. The initial points were chosen on the criteria that the height (altitude) is near to the operating point and for the angles it is preferred that it is kept between the range of +/- 1.57 rad (90˚) for roll and pitch and for yaw about +/- 3.14 (180˚) which in turn also be critical for the coupled translational motions if different from the range.

Table 2: PID gain turning table

| | Throttle | Roll angle | Pitch angle | Yaw angle |
|---|---|---|---|---|
| $K_P$ | 190 | 0.00345 | 0.00365 | 0.000795 |
| $K_I$ | 7 | 0 | 0 | 0 |
| $K_D$ | 90 | 0.00129 | 0.00128 | 0.000321 |
| % Overshoot | No Overshoot | 6 | 10 | 15 |

The altitude takes about 2 seconds to settle whereas the angles were stabilized in less than 1 seconds. The angles has a degree of accepted overshooting and doesn't get the desired angles. It can also be observed that the quadrotor throttle response at 5m that the quadrotor system overshoot at certain percentage before it's become stable.

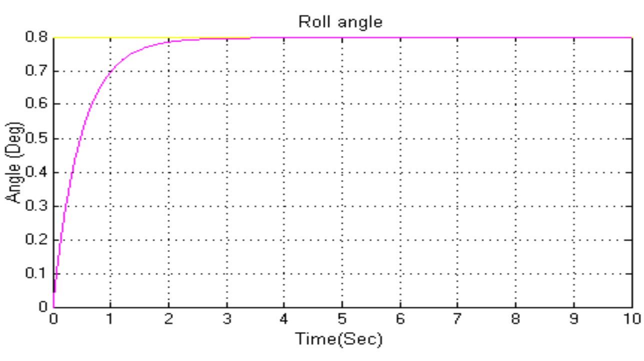


Figure 10: Roll Fuzzy-PID design response

From fig. 8, the quadrotor response to a command called throttle, shows that the time response to throttle command is very fast and without any overshooting for Fuzzy-PID controller while that of the PID controller have small overshoot. Also from figs. 10 and 12, it can be observed that the roll and pitch command responses do not have any overshoots whereas for the classical PID, figs. 9 and 11 show a small overshoot. This indicate that the fuzzy logic PID controller has adjusted the $K_P$, $K_I$ and $K_D$ parameter successfully.

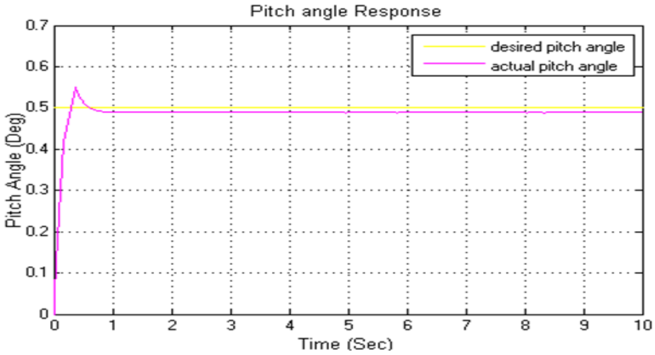


Figure 11: Pitch angle PID design response

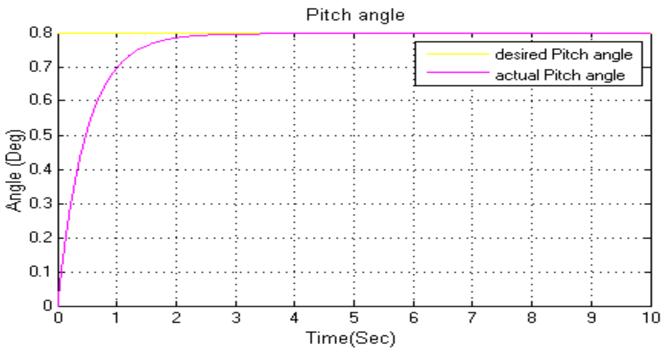


Figure 12: Pitch Fuzzy-PID design Response

## V. ANALYZING REAL-TIME QUADROTOR HELICOPTER USING DSPACE PLATFORM

Matlab/Simulink was used to simulate the nonlinear dynamic model of quadrotor to control the brushless DC motors. The experimental setup is shown in fig, 13 for a real time interface using dSPACE platform. The first block is a PWM signal block (Pulse Generator), the inputs being output voltage, signal frequency, and pulse-width as a percentage of signal frequency. The second block is the second transfer function and the third block is a dSPACE digital in/analogue out signal block, which takes the PWM signal and sent it to the motor controllers. Control Desk is then used to make a more useful control system. After building the model in Simulink, the parameters are linked in the PWM signal block to the control desk. A user-friendly layout is designed to make testing easier. It consists of multiple components. An on-off button is used, which changes the output from 0 to 5 volts. There are three ways to change the pulse-width of the signal. A slide-wheel is used for rapid changes, while a numerical input is used for exact pulse-width values. Buttons are also used, set at exact pulse-widths.

The timing advance parameter is set to low producing slightly less thrust. However, the motors run cooler, with less amperage draw, will increase the working lifetime. This is done because the thrust produced is much more than is necessary for hover, so any added efficiency will only increase working time.

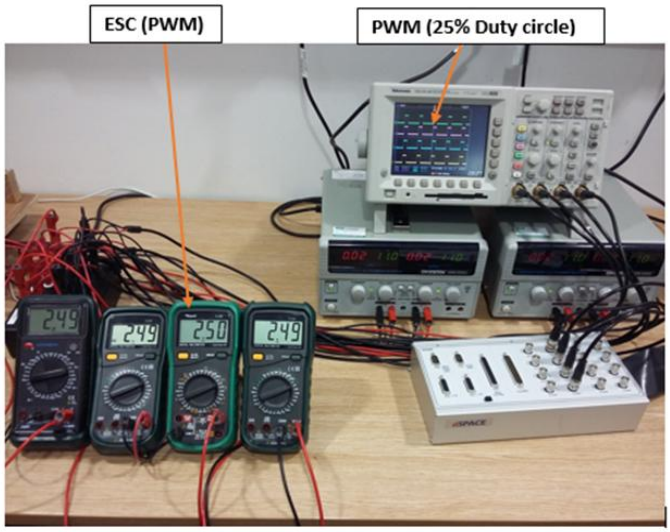


Figure 13: Real-time interface wave generation for quadrotor

On-board brushless motors via their pulse generator by change the duty cycle, a varying PWM signal is necessary. The PWM outputs are each, a square wave of 50 hertz with a high period of between 1 and 2 milliseconds, where 1ms is zero throttle, and 2ms is full throttle in a default configuration, for a fixed wing aircraft. Later on, the default setting was altered for one more suitable for a rotary wing aircraft, with a zero throttle at 1.3 milliseconds and full throttle at and above 1.8 milliseconds. Typically, for a servo actuator or reversible motor, 0-1 milliseconds signals are used for reverse motions of the motors rotor however.

## CONCLUSION

A Nonlinear dynamics Simulink model for Fuzzy- PID has been developed. The model verification was successful and it has been seen that the modelled dynamics faithfully responds to the commanded inputs. Right after the verification of the model; to include the rest of the other Euler angles that make up the attitude of the rotorcraft and stabilize the altitude together with the attitude with a classical controller (PID). With this controller the directly actuated degrees of freedom have been stabilized.

The developed FPID has implemented using a Real Time Interface dSPACE platform. The results so far have been successful in term of driving the quadrotor motors at the required speeds. However the feedback system from the motors is in a working progress for real time control to cater for external disturbances.

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