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FUZZY PID CONTROLLER FOR NANO-SATELLITE ATTITUDE CONTROL

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Abstract. *In this paper, a fuzzy PID controller has been suggested to use in attitude determination and control subsystem of kufasat equipped with three magnetic coils. Using the linearized equations of motion for a rigid body in space, the linearized stability, effectiveness and robustness of a fuzzy PID controller design were compared with that of a fuzzy PD controller design. The detailed design procedure of the fuzzy controllers is presented. When fuzzy PID controller is applied simulation results show that more precise attitude control is accomplished and less time of satellite maneuver is required comparing with applying fuzzy PD controller.*
Keywords: *Fuzzy PID Controller; Attitude Control System; Nanosatellite; KufaSat.*

1. INTRODUCTION

The attitude determination and control subsystem (ADCS) is responsible of keeping the orientation of spacecraft in the space in addition to achieve the required maneuver. Keeping the orientation of spacecraft in the space called attitude stabilization. The attitude maneuver is the re-orientation process of changing one attitude to another. The ADCS collects the data from attitude sensors and process it to determine the current attitude of spacecraft. The ADCS then compares the current attitude with the desired attitude and use the difference between them by help of specified algorithm to activate appropriate actuators to remove or reduce the error. There are some control techniques available to use in the controller. Proportional-Integral-Derivative (PID) controller is the most widely used controller with feedback mechanism. It is one of the simplest control algorithms, so it is often the best choice in many applications [1]. The linear quadratic regulator (LQR) from optimal control theory is another control technique which expresses the control problem as a mathematical optimization, and it then looks for the best controller and used state-space approach to analyze such a system. Other control technique is based on fuzzy logic and does not need a mathematical model of the system, instead it use Linguistic rules to represent the knowledge, these rules come from an actual human expert who know how best to control the process [2]. This technique is suitable to the systems with complex or uncertain mathematics model.

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2. DYNAMIC MODEL

The mathematical model of a satellite is described by the dynamic and kinematic equations of motion [3] .The general mathematical dynamic model of the satellite in low earth orbit can be obtained as:

$$^{b}T = I\,\dot{\omega}_{b/I} + {}^{b}\omega_{b/I} \times \left(I\ {}^{b}\omega_{b/I}\right) \tag{1}$$

where

I represent the moment of inertia matrix refer to body frame , $I = \mathrm{diag}[I_x \quad I_y \quad I_z]$.

$^{b}\omega_{b/I}$ is the angular velocity of body frame relative to an inertial frame.

^{b}T is total torque acting on satellite including gravity gradient torque, magnetic torque and other disturbance torque expressed in body frame components .

$$^{b}T = {}^{b}T_G + {}^{b}T_m + {}^{b}T_D \tag{2}$$

Equation (1) can be expanded in components to three dynamic equations for the roll, pitch, and yaw axes respectively as follows:

$$T_x = \dot{\omega}_x I_x + \left(I_z - I_y\right)\omega_y\omega_z \tag{3a}$$

$$T_y = \dot{\omega}_y I_y + (I_x - I_z)\omega_z\omega_x \tag{3b}$$

$$T_z = \dot{\omega}_z I_z + \left(I_y - I_x\right)\omega_x\omega_y \tag{3c}$$

where I_x, I_y, I_z are the moment of inertia and ω_x, ω_y, ω_z are angular velocities of body frame and T_x, T_y, T_z are the torques components vector acting on the body. These three equations represent Euler's equations of motion for a rigid body [4]. If the Euler angles ϕ, θ, ψ are small then, the relationship between Euler angular velocities and body angular velocities may be approximated [5] as,

$$\begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} = \begin{bmatrix} \dot{\phi} + \omega_o\psi \\ \dot{\theta} - \omega_o \\ \dot{\psi} - \omega_o\phi \end{bmatrix} \tag{4}$$

2.1 GRAVITY GRADIANT TOURQUE

The gravity gradient torque, using a small Euler angle approximation and taking principal axes as reference axis is given [6] by:

$$\left.\begin{aligned} T_{Gx} &= 3\omega_o^2\left(I_z - I_y\right)\varphi \\ T_{Gy} &= 3\omega_o^2\left(I_z - I_x\right)\theta \\ T_{Gz} &= 0 \end{aligned}\right] \tag{5}$$

where T_{Gx} ,T_{Gy} ,T_{Gz} are the gravity gradient torque about the Roll , Pitch , Yaw axis, respectively .

2.2 MAGNETIC FIELD TORQUE

When the current flow through windings of the magnetic coil a magnetic dipole will be produced which is proportional to the ampere-turns and the area enclosed by the coil. The torque generated by the magnetic coils can be modeled as:

$$T_m^b = m^b \times B^b \tag{6}$$

where m^b is the generated magnetic moment inside the body and $B^b = \left[B_x^b \; B_y^b \; B_z^b\right]^T$. is the local geomagnetic field vector

$$m^b = m_x^b + m_y^b + m_z^b = \begin{bmatrix} N_x i_x A_x \\ N_y i_y A_y \\ N_z i_z A_z \end{bmatrix} = \begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix}$$

where N_k is number of windings in the magnetic coil, i_k is the coil current and A_k is the span area of the coil. The magnetic torque can be represented as:

$$\begin{bmatrix} T_{mx} \\ T_{my} \\ T_{mz} \end{bmatrix} = \begin{bmatrix} m_y B_\psi - m_z B_\theta \\ m_z B_\varphi - m_x B_\psi \\ m_x B_\theta - m_y B_\varphi \end{bmatrix} \tag{7}$$

where T_{mx} , T_{my} , T_{mz} are the magnetic torque and m_x , m_y , m_z are the corresponding of the magnetic moments and B_φ , B_θ , B_ψ is the earth's magnetic . By adding equation (5) and equation (7) to equation (3) the final form of linearized attitude dynamic model of the satellite including gravity gradient torque and magnetic coil torque written in body frame components becomes

$$\ddot{\phi} = \left(-\frac{4\omega_0^2(I_y - I_z)}{I_x}\right)\phi + \left(\frac{\omega_0(I_x - I_y + I_z)}{I_x}\right)\dot{\psi} + (m_y B_\psi - m_z B_\theta)/I_x \quad \text{(Roll)} \tag{8a}$$

$$\ddot{\theta} = \left(-\frac{3\omega_0^2(I_x - I_z)}{I_y}\right)\theta + (m_z B_\varphi - m_x B_\psi)/I_y \quad \text{(Pitch)} \tag{8b}$$

$$\ddot{\psi} = \left(-\frac{\omega_0^2(I_y - I_x)}{I_z}\right)\psi - \left(\frac{\omega_0(I_x - I_y + I_z)}{I_z}\right)\dot{\phi} + (m_x B_\theta - m_y B_\varphi)/I_z \quad \text{(Yaw)} \tag{8c}$$

3. FUZZY LOGIC CONTROLLER DESIGN

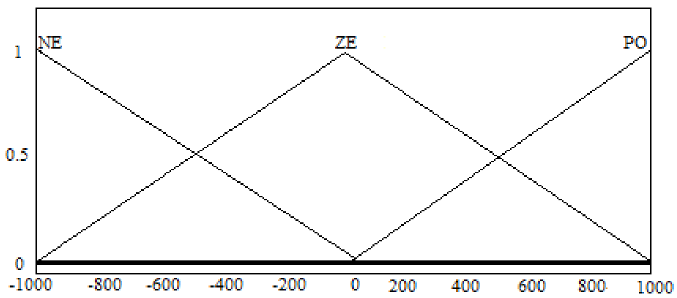
Three coils are installed on body of the satellite one on each axis. These coils can be fed with a constant current with two directions to generate a magnetic dipole moment M. This magnetic dipole moment interacts with the geomagnetic field vector B to generate a torque N by taking the cross product [7]:

$$N = M \times B \tag{9}$$

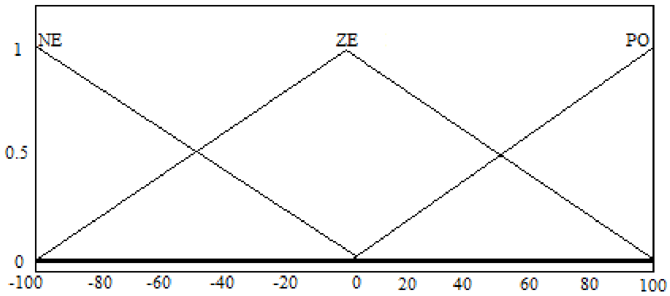
This torque is used to control the rotation of the satellite. Three Takagi-Sugeno fuzzy logic controllers (FLC), one for each coil, are used to control each coil's current polarity and switching (on, off). Each FLC has nine rules and three linguistic variables which are for its two inputs, error (E) and change-in-error (CE), and its one output (U) [8]. Each variable (E, CE, and U) is then represented by a membership function, as show in Figure 1. The output of the three FLCs which represents the control action is used to control the roll, pitch, and yaw angles, respectively, through the associated coil current. Linguistic variables which imply inputs are mapped into three fuzzy set Positive (PO), Negative (NE) and Zero (ZE) rules. The output variable indicates the desired magneto-torquer polarity, (HI) for positive polarity and (LO) for negative polarity. These rules which contain the input/output relationships that define the control strategy are shown in Table (1).

Table 1. Rule base for the controller of Roll, Pitch, and Yaw

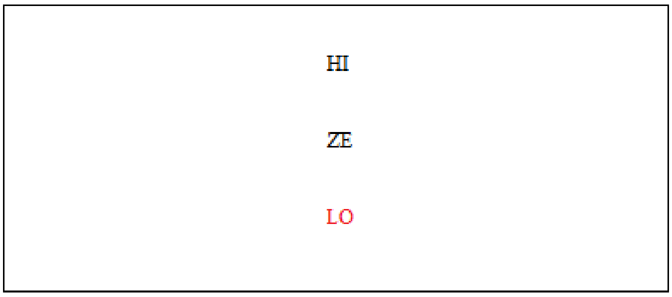
Error \ Change of Error	NE	ZE	PO
NE	LO	LO	ZE
ZE	LO	ZE	HI
PO	ZE	HI	HI



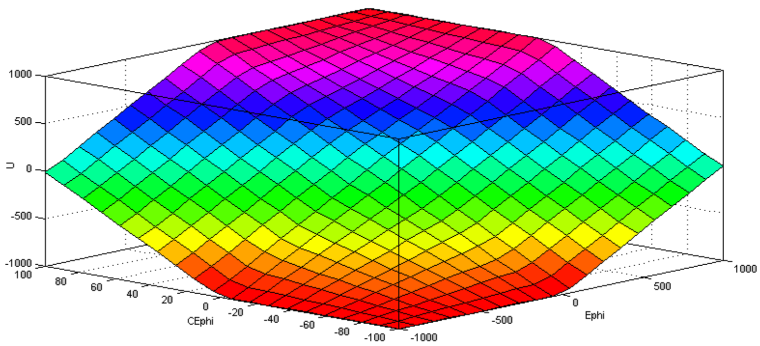
a) Membership Function for Ephi (Error)



(b) Membership Function for CEphi (Change of Error)



(c) Output U



(d) Control surface between inputs and output variable

Figure 1. Membership functions used in FLC for (a) Error E, (b) Change of error CE, (c) Output U, and (d) Control surface

Two structures for fuzzy controller have been proposed in this paper, fuzzy PD, and fuzzy PID which is implemented as fuzzy PD + I controller [9]. Each one of the proposed controllers has two inputs and one output. These are error, change of error and control signal, respectively. The block diagram of these controllers is shown in Fig. 2 and Fig. 3.

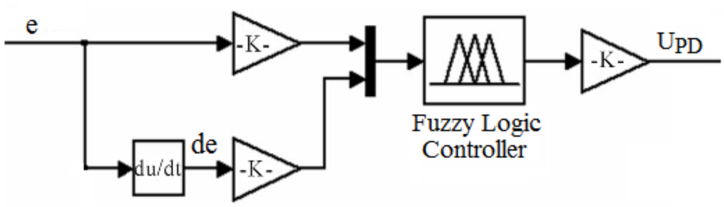


Figure 2. Block diagram of the fuzzy PD controller.

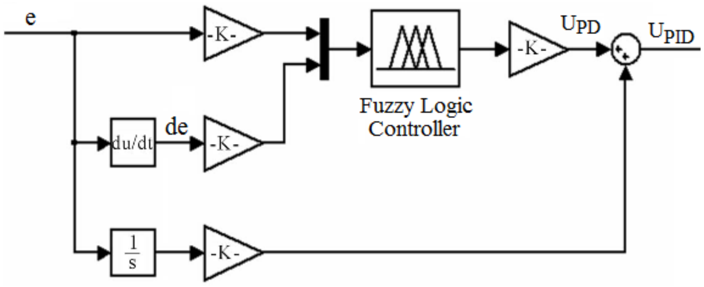


Figure 3. Block diagram of the fuzzy PID controller.

4. SIMULATION AND RESULTS

In this paper, several simulations of the proposed controllers have been done. The parameters values used for kufasat are listed in Table (2) [10]:

Table 2. KufaSat parameters

Parameter	Value
Orbit	LEO, altitude of 600 km, inclination $=97^o$
Period	96.684minutes
Mass and Dimensions	1.3 kg 10×10×10 cm
Moments of inertia	Ix = 0.1043, Iy= 0.1020, Iz = 0.0031 kgm^2
Boom length and Tip mass	1.5 m 40g
Orbit angular velocity	1.083*10^-3 rad/sec
Maximum magnetic moment	0.1 Am2
Magneto-torquer	3 perpendicular magnetic coils
Desired Euler angle values [φ θ ψ]	[0 0 0]

4.1. STABILIZATION TEST

In this test, (0 to 1) rad step input was applied on two proposed controllers, first using fuzzy PD controller and second using fuzzy PID controller. Figure 4 show the system response when using fuzzy PD and fuzzy PID controllers, when the initial conditions of the roll, pitch, and yaw angles are equal to (0, 0, 0) degrees.

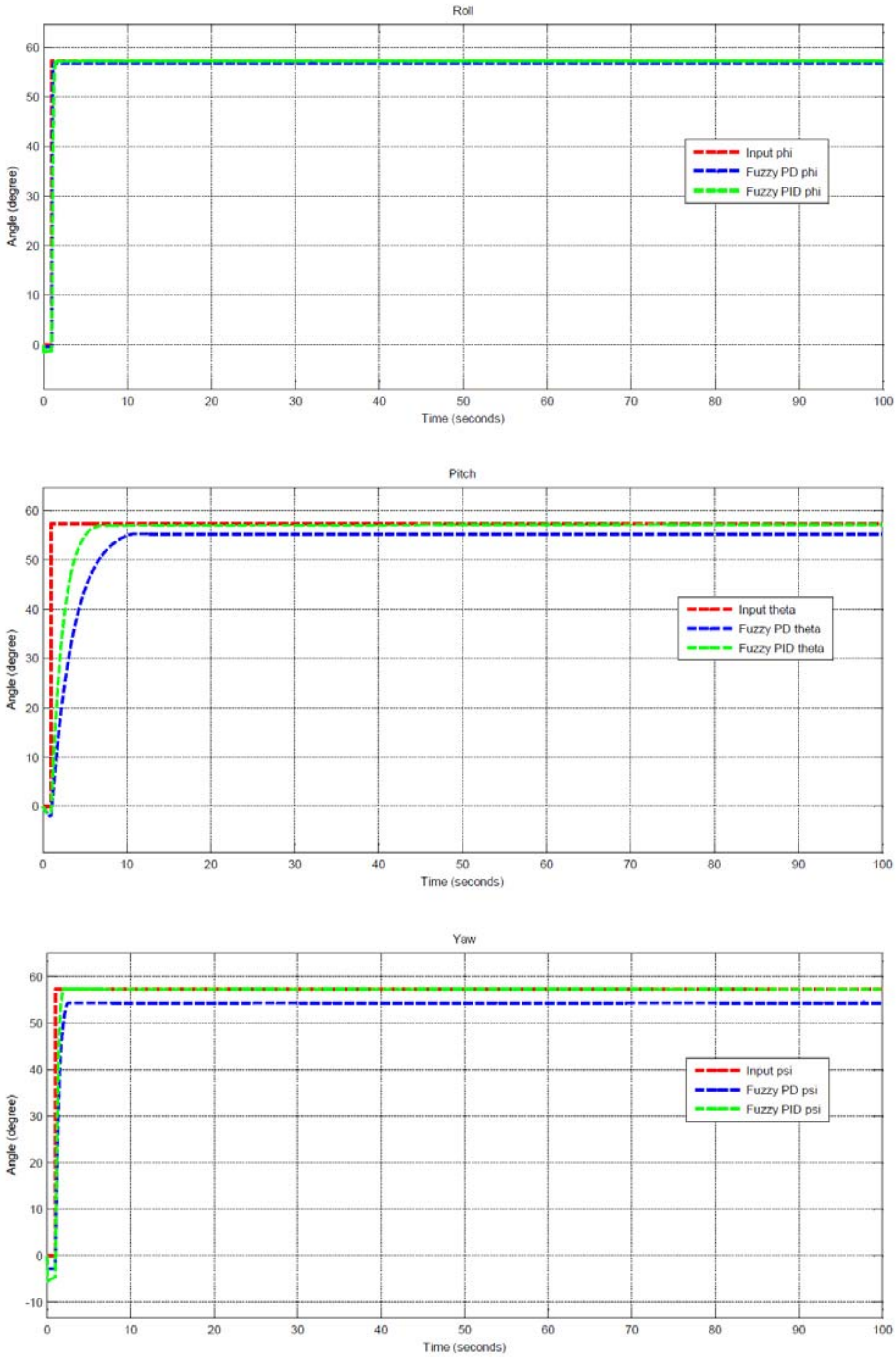


Figure 4. Angular position as a function of time using fuzzy PD and fuzzy PID controllers with 1 rad step input.

4.2. ATTITUDE CONTROL MANEUVER (ACM) TEST

In this section, the fuzzy PD and fuzzy PID controllers are tested to achieve different orientations. Figures 5and 6 illustrate Kufasat attitude response to a small and a large ACM with fuzzy PD and fuzzy PID controllers.

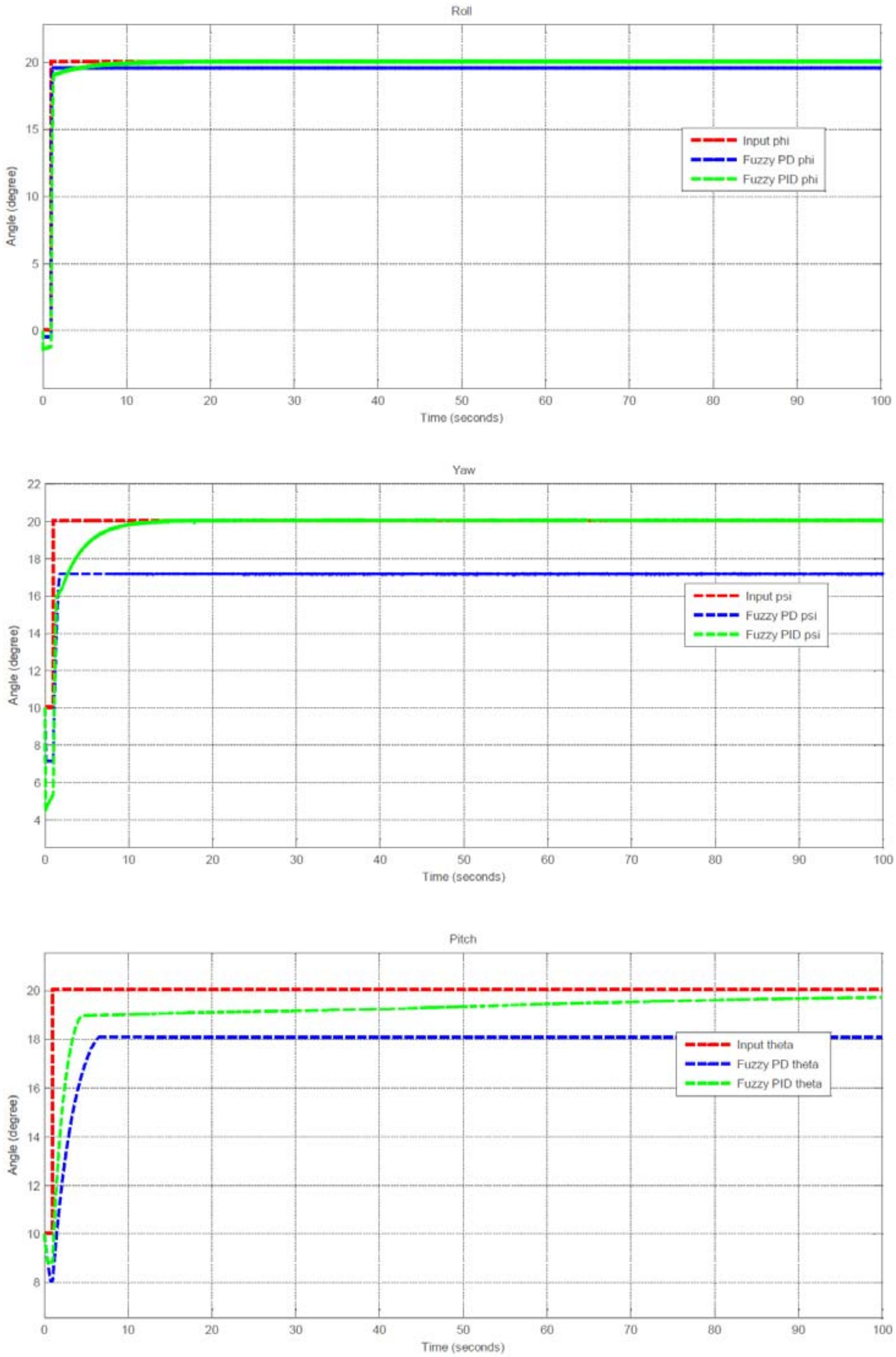


Figure 5. Response to a small ACM from [0° 10° 10°] to [20° 20° 20°] using fuzzy PD and fuzzy PID controllers.

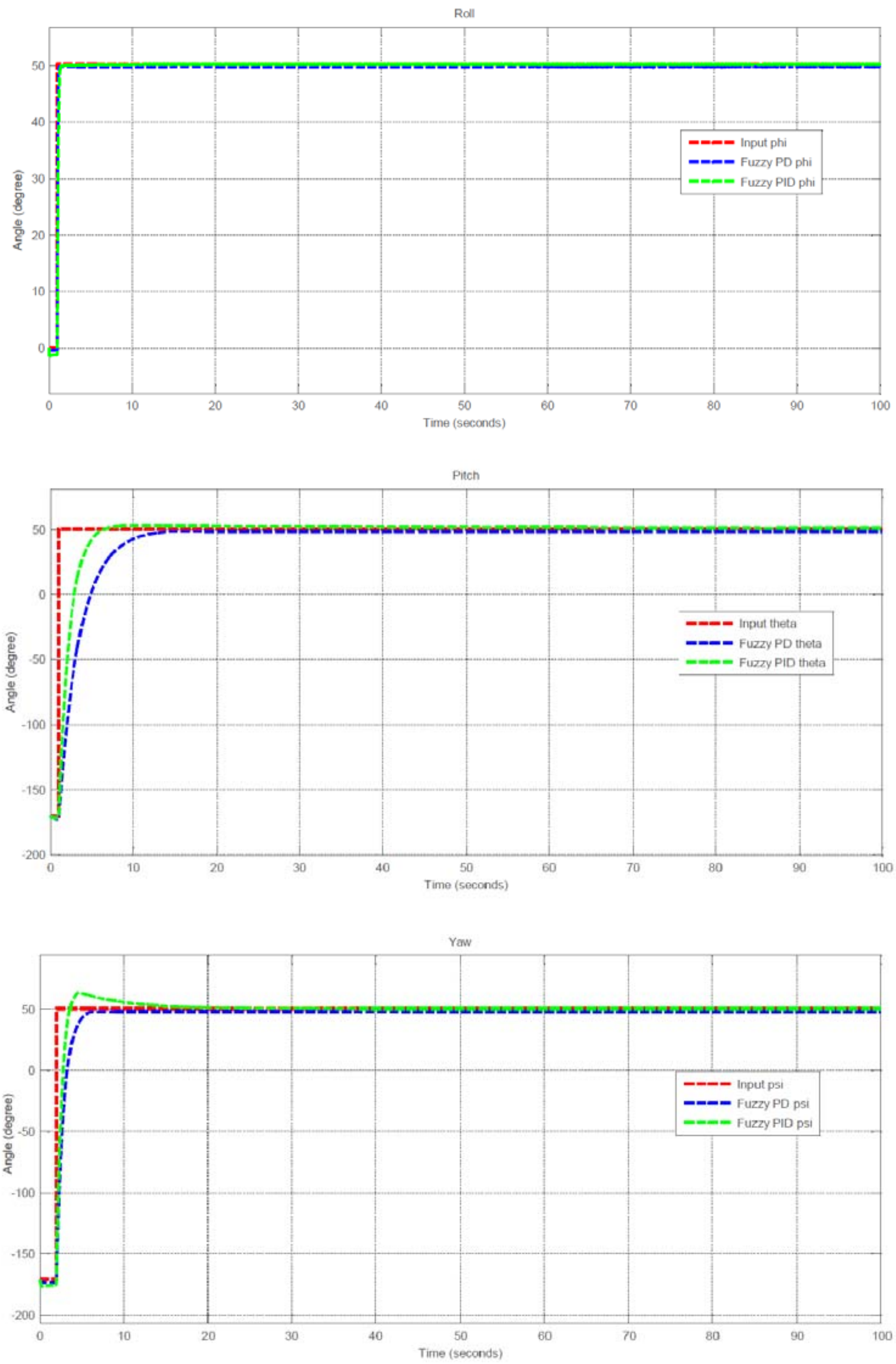


Figure 6. Response to a large ACM from [0° -170° -170°] to [50° 50° 50°] using fuzzy PD and fuzzy PID controllers.

5. CONCLUSIONS

In this paper, fuzzy PID controller for attitude control of kufasat equipped with three magnetic coils is developed and its performance compared with fuzzy PD controller. From the simulation results it is observed that the fuzzy PID controller was able to meet the design goals, and has better performance in terms of error steady state, settling time, and rise time. Furthermore fuzzy PID controller is controllable and more stable than fuzzy PD controller and has shorter time of maneuver when the system is under effect of AMC.

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