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Fuzzy-PID Controller for Azimuth Position Control of Deep Space Antenna

Halima S. Yakubu, Suleiman U. Hussein, Gokhan Koyunlu, Essien Ewang & Sadiq U. Abubakar

Nile University of Nigeria, Abuja, Nigeria
Centre for Satellite Technology Development, Obasanjo Space Centre, Abuja, Nigeria
halima.syakubu@gmail.com, elsuligh@gmail.com

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Abstract— Abstract: The Deep Space Antennas are essential in achieving communication over very large distances. However, the pointing accuracy of this antenna needs to be as precise as possible to enable effective communication with the satellite. Therefore, this work addressed the pointing accuracy for a Deep Space Antenna using Fuzzy-PID control technique by improving the performance objectives (settling time, percentage overshoot rise time and mainly steady-state error) of the system. In this work, the PID controller for the system was first of all designed and simulated after which, a fuzzy controller was also designed and simulated using MATLAB and Simulink respectively for the sake of comparison with the fuzzy-PID controller. Then, the fuzzy-PID controller for the system was also designed and simulated using MATLAB and Simulink and it gives a better performance objective (rise time of 1.0057s, settling time of 1.6019s, percentage overshoot of 1.8013, and steady-state error of 2.195e-6) over the PID and fuzzy controllers respectively. Therefore, the steady state error shows improved pointing accuracy of $\pm$2.195e-6.

Keywords/Index Terms— azimuth position control, deep space antenna, fuzzy logic control, fuzzy-PID, PID controller, pointing accuracy.

1. Introduction

The significance of pointing accuracy cannot be overemphasised as the development of radar and satellite systems progresses, and thus, the need to produce better control results with improved control techniques have become of great importance especially in communication industries. Communication over very large distances (e.g., deep space communication) is achieved by means of satellite communication. This can be established and maintained if the constellation of the communication satellites ensures that it is always possible to make contact with satellite, irrespective of the actual position on Earth.

Position control systems have, in recent years, been used extensively in applications such as in robotics, antennas, automation and many others . Amongst the most common and traditional techniques for position control is the Proportional-Integral-Derivative (PID) controller. Its straightforward configuration makes it easy to comprehend and its satisfactory performance causes it to maintain its status as the most widely used controller in industrial control system. However, the major challenges with the use of conventional PID are the tuning of the parameters and effect of non-linearity in the plant.

Therefore, Fuzzy Logic Control (FLC) which has the capacity of overcoming the issue of non-linearity in a plant can be considered. Furthermore, the exact mathematical model of a plant is not necessary when FLC is applied for the control of the system. However, the accuracy of the controller is subject to the expertise of the designer, which ultimately might impede the performance of the control system.

A technique which incorporates the concepts of both Fuzzy Logic and PID control, the Fuzzy-PID control, is explored. Fuzzy-PID is considered an extension of the conventional PID as it preserves the linear structure of the controller.

Several control methods have been proposed in literature for the position control of deep space antenna. For example, in the work of Okumuş *et al.* (2012), antenna azimuth position was controlled using two different controllers; classical PID and FLC that was tested with various fuzzy rules and membership functions. Results from both controllers were compared and the FLC was seen to give better results however, it requires high computational power to function. Also, Sahoo and Roy (2014), proposed a robust Quantitative Feedback Theory (QFT) controller which was designed for a 2-Degree of Freedom (DOF) azimuth position control of antenna with parametric uncertain. The QFT controller produced good results in terms of performance and stability specification but did not take into consideration system disturbances such as noise. In Zaber *et al.* (2015), a position control scheme of a Radio Telescope Antenna with wind disturbance using PID was presented. Although the controller succeeded in attenuating wind disturbances acting upon the radio telescope model however, better results could have been achieved using a more robust control technique. In addition, Fandaklı and Okumuş (2016) designed three different controllers (PID, Fuzzy Logic and Sliding Mode Control) for the azimuth position control of deep space antenna and compared their results in terms of performance. The results shows that the Sliding Mode Controller (SMC) outperformed the other controllers in terms of settling time and low sensitivity to noise disturbance, however modifications were not made to reduce chattering which is inherent in SMCs. However, in the work of E. G. Kumar (2018), the position control of the antenna azimuth was investigated using Proportional Integral (PI) and Fractional Order Lead Compensator controllers. Though the proposed lead compensator outperforms the PI controller when considering closed loop performances like response speed and settling time, it however had a high frequency gain, which amplifies the high frequency noise.

The robustness and efficiency of fuzzy-PID controller have been established in literatures for the DC motor control speed and Permanent Magnet (PM) synchronous motor. This controller also finds application in Automatic Generation Control (AGC) for multi-area interconnected power system (Mohanty *et al.* 2016). It can be used for the control of wind turbine pitch angle in (Civelek *et al.* 2016). Furthermore, it can be applied for the control of autonomous underwater vehicle (AUV) in heading and depth altitude and many others.

Therefore, in this work, the fuzzy-PID controller for azimuth position control of deep space antenna has been proposed.

The outline of the paper is as follows: system description, fuzzy-PID controller design, results and discussion, and the conclusion.

2. System Description

In this section, concepts such as antenna position system modelling of DC motor are discussed.

2.1. *Antenna Position System*

In position control systems, position input signals are converted to position output responses. For deep space antenna control, the aim is to make the antenna azimuth $\theta_0(t)$ track the reference $\theta_i(t)$ as much as possible by minimizing the tracking error.

A typical antenna should be able to rotate around azimuth (vertical) and elevation (horizontal) axes. These movements are independent, and their control systems are independent as well. The movement and rotation of the antenna are controlled by elevation and azimuth controllers respectively.

Figure 1 shows the control diagram of the antenna azimuth which represented servo-controlled mechanism with gears and feedback potentiometers.

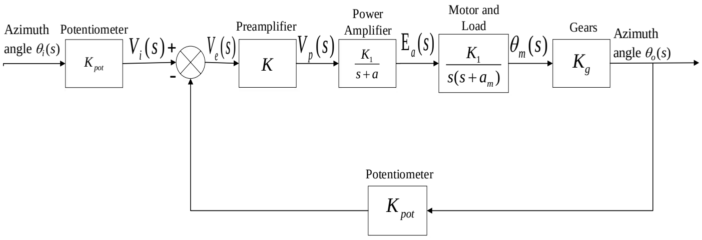

FIGURE 1: A CLOSED-LOOP ANTENNA AZIMUTH POSITION CONTROL FOR DEEP SPACE ANTENNA

The closed-loop control diagram of the azimuth position control is shown in Figure 1. The input is an angular displacement which is converted into a voltage signal by a potentiometer. Similarly, the output angular displacement is also converted to a voltage signal for the feedback by the potentiometer. An error signal is generated at the comparator as a result of the difference between the input and output signals. Next, a differential amplifier checks the magnitude of the error as a result of the difference and passes it to the signal and power amplifiers which amplify the signal accordingly in order to drive the system. The aim of the controller for the system is to drive the error to zero or as close as possible. When this is achieved the motor will not turn. The greater the error signal is, the higher the input voltage of the motor, which in turn makes the motor rotate faster. DC servo motor which is armature controlled is used for this system.

2.2. *Modelling of DC Motor*

DC motor that is armature controlled was chosen due to its high starting torque and relatively cheaper cost. The equivalent circuit of a DC motor with an armature controlled is shown in Figure 2.

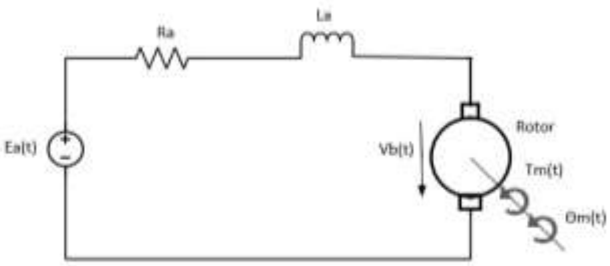

FIGURE 2: EQUIVALENT CIRCUIT DIAGRAM OF THE ARMATURE CONTROLLED DC MOTOR

The dynamics of the electrical and mechanical subsystems of the armature controlled DC motor are given in Equations (1) to (6).

$$V_b = K_b \frac{dq_m}{dt} \quad (1)$$

$$R_a i_a(t) + L\frac{di_a(t)}{dt} + V_b(t) = E_a(t) \quad (2)$$

$$T_m = K_t i_a(t) \quad (3)$$

$$T_m = J_m \frac{d^2\theta_m}{dt^2} + D_m \frac{d\theta_m}{dt} \quad (4)$$

$$J_m = J_a + J_L\left(\frac{N_1}{N_2}\right)^2 \quad (5)$$

$$D_m = D_a + D_L\left(\frac{N_1}{N_2}\right)^2 \quad (6)$$

The parameters and units used in Equations (1) – (6) are given in Table I.

TABLE I: PARAMETERS OF THE ANTENNA DYNAMICS

Parameter	Definitions	Values
V	Potentiometer voltage (V)	10
L	Motor inductance (H)	0.01
n	Potentiometer turns	10
K_1	Amplifier Gain Power	100
a	Pole of Power amplifier	100
R_a	Motor Resistance (Ω)	8
J_a	Motor inertial constant (kg-m2)	0.02
D_a	Motor Damping Constant (N-m s/rad)	0.01
K_b	Back EMF (V-s/rad)	0.5
K_t	Motor Torque Constant (N-m/A)	0.5
N_1, N_2, N_3	Gear teeth	25, 250, 250
J_L	Inertial constant of the load (kg-m2)	1
D_L	Load inertial constant (N-m s/rad)	1
K_{pot}	Gain of the Potentiometer	0.318
K_m	Load gain with motor	2.083
a_m	Pole of motor and load	1.71
K_g	Gear ratio	0.1

E_a - voltage across the motor (V)
θ_m - angular displacement of the motor (degree)
i - circuit current (A)
R - motor resistance (Ω)
T_m - motor torque (Nm)
V_b - voltage across the rotor (back emf) (V)
J - inertia of the motor rotor and load (Nms^2/rad)
D - damping of the motor rotor and load (Nms/rad)
L - armature inductance (H)
K_t - torque constant (Nm/A)
N - gear teeth

Through a series of substitutions using Equations (1) to (6), a mathematical expression of the armature controlled DC motor with respect to the output, θ_m to the input, E_a is derived and is given in Equation (7) as

$$K_b \frac{d\theta_m}{dt} = E_a - \frac{R_a}{K_t}\left(J_m \frac{d^2\theta_m}{dt^2} + D_m \frac{d\theta_m}{dt}\right) - \frac{L}{K_t}\left(J_m \frac{d^3\theta_m}{dt^3} + D_m \frac{d^2\theta_m}{dt^2}\right) \quad (7)$$

Equation (7) is then modelled using MATLAB and Simulink in Figure 3.

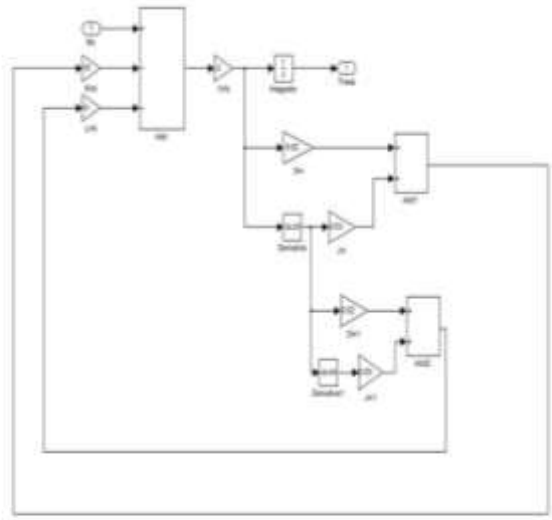

FIGURE 3: SIMULINK MODEL OF ARMATURE CONTROLLED DC MOTOR

3. FUZZY-PID CONTROL DESIGN

Firstly, we begin with the design of a fuzzy logic controller (FLC).

Lotfi A. Zadeh was the first to introduce fuzzy logic but was only later implemented by E. H. Mamdani almost ten years after its introduction. FLC have a wide range of applications in areas like industrial manufacturing and automation, automobile production, hospitals, banks, libraries and academic education, etc.

The basic structure of FLC system is shown in Figure 4. It comprises of four basic elements, which are: fuzzy knowledge base, fuzzification interface, inference engine (decision-making logic), and defuzzification interface.

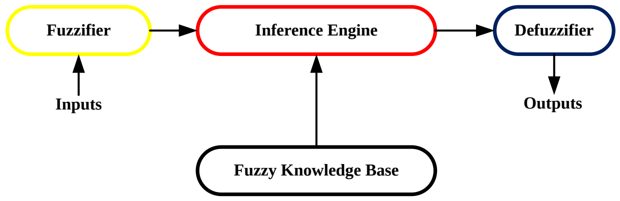

FIGURE 4: BASIC STRUCTURE OF A MAMDANI-TYPE FUZZY LOGIC SYSTEM

3.1. *Fuzzification*

Here, the crisp inputs, 'error (E)' and 'change in error (CE)', are fuzzified, i.e. converted into fuzzy variables. In this research work, triangular membership function was selected for the inputs and output variables with its crossing μ = 0.5. The leftmost and rightmost fuzzy sets (with respect to inputs and output) are represented as shouldered ramps. The inputs and output are defined on a universe of discourse which was divided into 5 overlapping fuzzy sets: sets Negative Small (NS), Negative Large (NL), Zero (Z), Positive Large (PL), and Positive Small (PS). Figure 5 and Figure 6 show the two input variables for the fuzzy controller. The single output of the fuzzy controller is defined similarly to the inputs and is shown in Figure 7.

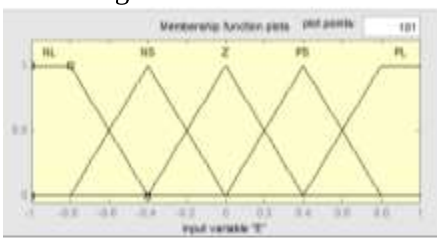

FIGURE 5: 'ERROR (E)' INPUT VARIABLE

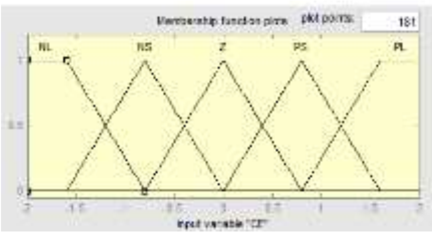

FIGURE 6: 'CHANGE IN ERROR (CE)' INPUT VARIABLE

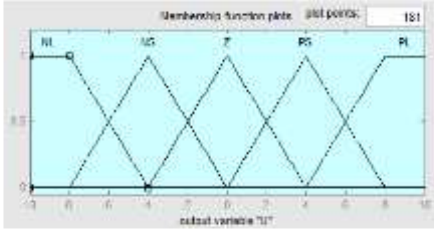

FIGURE 7: 'U' OUTPUT VARIABLE

3.2. *Inference Engine*

It is knowledge base where rules are defined as if-then statement that guides the relationship between the input and output variables in terms of membership functions. At this level, the inference engine processes E and CE which executes 25 rules (5x5) as shown in Table II, where max-product inference method is used. The weight of all the rules is given as 1 (which actually has no effect on the implication process).

TABLE II: FUZZY RULE BASE FOR CONTROLLER DESIGN

CE/E	NL	NS	Z	PS	PL
NL	NL	NL	NL	NS	Z
NS	NL	NS	NS	Z	PS
Z	NL	NS	Z	PS	PL
PS	NS	Z	PS	PS	PL
PL	Z	PS	PL	PL	PL

3.3. *Defuzzification*

This stage entails the generation of a usable output for the control of the system. Here, the internal fuzzy output variables are converted by the FLC into crisp values that can actually be used by the control system. Bisector method is used for defuzzification. The outputs are singletons, whose positions were derived by the cumulative of peak positions of the input sets.

Next, the PID controller is designed and tuned. Figure 8 shows the Simulink model of the fuzzy-PID configuration.

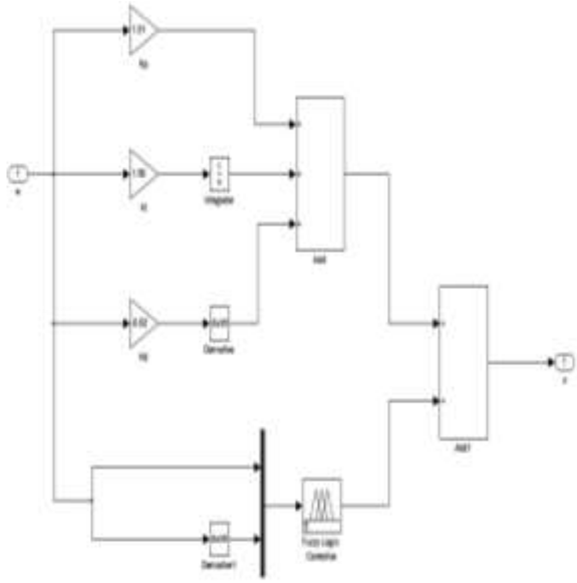

FIGURE 8: SIMULINK MODEL OF THE FUZZY-PID CONFIGURATION

Figure 9 shows the Simulink model of the antenna with FLC for the azimuth position control of the system.

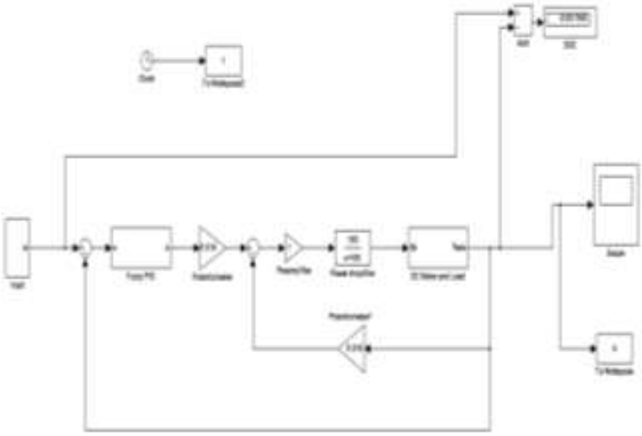

FIGURE 9. SIMULINK MODEL OF THE ANTENNA WITH FUZZY-PID CONTROLLER

The response of the fuzzy-PID controller was compared with that of the fuzzy logic and Proportion-Integral-Derivative (PID) controllers to determine its performance. Therefore, PID controller was first of all designed in MATLAB and Simulink to control the system after which the FLC was designed, and finally the fuzzy-PID controller was then designed for the antenna system.

4. Results and Discussion

In this section, the responses of the deep space antenna with respect to the three different controllers are presented here.

4.1. Response of Deep Space Antenna with PID Controller

Figure 10 shows the step response of the antenna position system with PID controller.

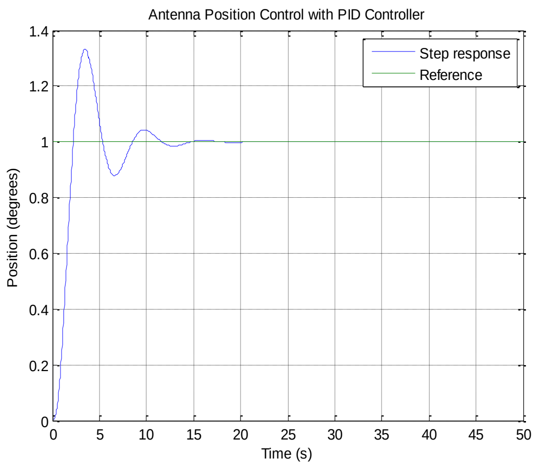

FIGURE 10: UNIT STEP RESPONSE OF THE DEEP SPACE ANTENNA WITH PID CONTROLLER

TABLE III: PARAMETERS OF THE PID CONTROLLER

Parameter	Value
Rise Time	1.3726s
Settling Time	10.9478s
Overshoot	33.1750%
Peak Time	3.4675s
Steady-state Error	1.368e-007

From Table III above, it evident that the PID controller has a rise time of 1.3726s, and a lower steady-state error which is indicative of a high pointing accuracy. However, the PID controller has an overshoot of 33.1750% which is much higher than the accepted value of between 0 and 10%, and a large settling time which makes the PID an undesirable controller. The large overshoot could lead to actuator (motor) damage during the transient state of the deep antenna operation.

4.2. Response of Deep Space Antenna with Fuzzy Logic Controller

Figure 11 shows the step response of the antenna with respect to the azimuth position control with FLC.

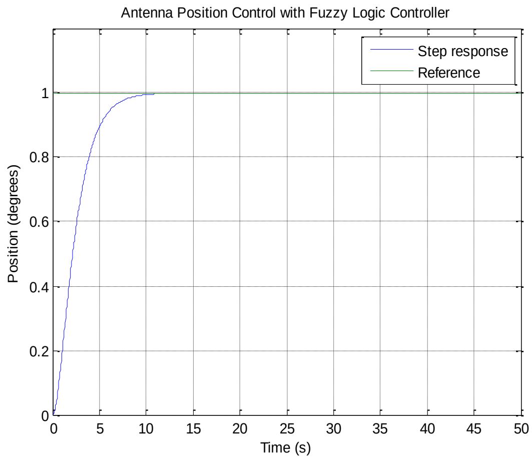

FIGURE 11: FIGURE XI. STEP RESPONSE OF SYSTEM WITH FUZZY LOGIC CONTROLLER

TABLE IV: FUZZY CONTROLLER PARAMETERS

Parameter	Value
Rise Time	4.3381s
Settling Time	7.4146s
Overshoot	0%
Peak Time	10s
Steady-state Error	0.004358

Table IV shows the fuzzy controller performance with an overshoot of 0% and a settling time of 7.4146s which is highly favourable to the actuator (motor) for driving the gears of the deep space antenna. But 0.004358 steady state error is present which is also favourable. This implies that the pointing accuracy of the deep space antenna to a satellite would be ±0.004358m which is very good.

4.3. Response of Deep Space Antenna with Fuzzy-PID Control

Figure 12 shows step response of the antenna azimuth position control with fuzzy-PID controller.

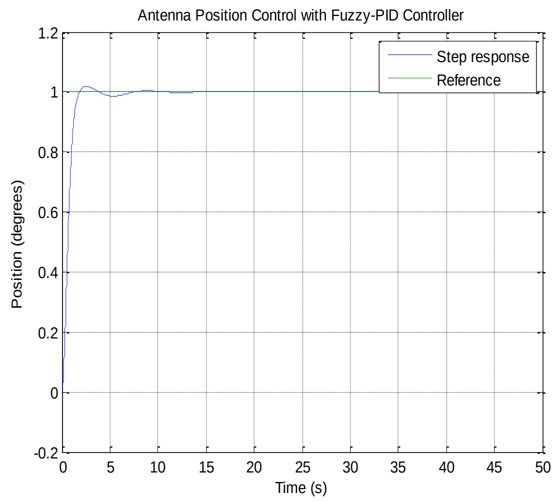

FIGURE 12: UNIT STEP RESPONSE OF THE ANTENNA WITH FUZZY-PID CONTROLLER

TABLE V: FUZZY-PID CONTROLLER PARAMETERS

Parameter	Value
Rise Time	1.0057s
Settling Time	1.6019s
Overshoot	1.8013%
Peak Time	2.6091s
Steady-state Error	2.195e-006

From Table V, it is evident that the fuzzy-PID controller has a fast rise time of 1.0057s and settling time of 1.6019s. It has an overshoot of 1.8013% which is acceptable for a control system. Also, the steady-state error implies a high pointing accuracy of $\pm 2.195e\text{-}006$m between the deep space antenna and the satellite which is very good.

4.4. Comparing the Response of the Fuzzy Logic and PID Controllers for the Deep Space Antenna

Figure 13 shows the comparison of the step response of the antenna with respect to the control of the azimuth position with PID, fuzzy and fuzzy-PID controllers.

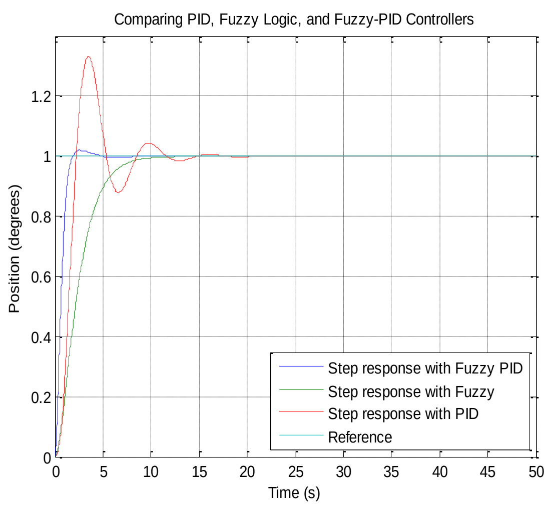

FIGURE 13: STEP RESPONSES OF AZIMUTH POSITION CONTROL WITH FUZZY-PID, FUZZY AND PID CONTROLLERS

Table VI gives the comparison of PID, fuzzy and fuzzy-PID controller with respect to performance.

TABLE VI. PERFORMANCES COMPARISON OF PID, FUZZY AND FUZZY-PID CONTROLLERS

Parameter	PID	Fuzzy	Fuzzy-PID
Rise Time	1.3726s	4.3381s	1.0057s
Settling Time	10.9478s	7.4146s	1.6019s
Overshoot	33.1750%	0%	1.8013%
Peak Time	3.4675s	10s	2.6091s
Steady-state Error	1.368e-007	0.004358	2.195e-006

From Table VI, it shows that the PID controller has the best performance with respect to steady state error but a large overshoot and slow settling time undermines its overall performance. To put it further, an overshoot of 33.1750% is well above the prescribed value for a control system and is likely to cause a fault to the antenna system which will render the steady-state performance irrelevant.

The fuzzy controller performs better in terms of overshoot. However, the values of the rise time and settling time are large which implies a sluggish response of the system to the controller.

The fuzzy-PID controller has the best performance as regard settling time, rise time and peak time. It also has an acceptable overshoot of 1.8013% and a small steady-state error. These imply that the system exhibits a fast response and a high pointing accuracy.

It is clear that the fuzzy-PID controller outperforms the PID and fuzzy controllers if one considers the parameters of each controller relative to the other.

5. CONCLUSION

This work aimed at improving the Azimuth Position Control of a Deep Space Antenna by increasing the pointing accuracy through a small steady-state error and very low overshoot. From the work done, it shows that the fuzzy-PID controller (out of all the controllers used) has the best performance to achieve this aim.

A PID controller for the system was first of all designed and simulated in this research work, after which a fuzzy controller was also designed and simulated using MATLAB and Simulink respectively for the sake of comparison with the fuzzy-PID controller. Then, the fuzzy-PID controller for the system was also designed and simulated using MATLAB and Simulink and it gives the best performance objectives (rise time of 1.0057s, settling time of 1.6019s, percentage overshoot of 1.8013, and steady-state error of 2.195e-6) over the PID and fuzzy controllers.

The contribution to knowledge of this work is the improved pointing accuracy of $\pm 2.195e\text{-}6$ using fuzzy-PID control that will enable the deep space antenna track the satellite.

5.1. *Further Work*

A fuzzy-PID controller tuned using heuristic methods such as Genetic Algorithm and neural networks for the control of deep space antenna can be looked into for improved performance.

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