Optimizing Antenna Azimuth Position Control using Fuzzy PD, Fuzzy PD-I, and Fuzzy PD-plus-I Controllers

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The fuzzy logic controller (FLC) is considered one of the most familiar control techniques for dealing with uncertain and nonlinear systems. However, the steady-state error is still a challenge in some applications that need to be handled. To diminish this issue, an integral part has been incorporated with the fuzzy controller. This paper examines three kinds of FLC systems to improve the accuracy of the antenna's azimuth position. The three proposed controllers: basic fuzzy PD logic control system (FPD), fuzzy logic control system with an I controller (FPDI), and fuzzy logic control system plus an I controller (FPD+I) are implemented and compared in case of tracking desired antenna angle, disturbances and uncertainties using MATLAB simulation software. It has been observed that the FPD+I controller part proved effective in reducing steady-state error while delivering the best tracking performance response of the antenna's azimuth position and robustness to disturbances and uncertainties.

Keywords: Antenna azimuth position; Fuzzy PD controller; Fuzzy PD-I controller; Fuzzy PD-plus-I controller; PID controller.

1. Introduction

Nowadays, Control systems play a crucial role in the modern world. They are essential for various operations and have become an integral part of our daily lives. Position control systems have become increasingly prevalent in various applications including different types of robotics, antennas, radar systems, automation systems, and many other real-world applications [1]–[4]. One of the most popular controllers in industrial control systems is the traditional PID controller due to its structure simplicity, adaptability, reliability, and good response[5]. However, conventional PID controller presents challenges in terms of parameter tuning and sensitivity to non-linearity in a controlled system[6]. This can result in decreased performance as system order increases and sensitivity to changes in system parameters. Therefore, alternative control techniques have been proposed to address these issues .

Over the past few decades, as the field of communications and wireless technologies has continued to evolve, there has been an increasing need for precise control over antenna azimuth positions to ensure optimal transmission and reception of data. Figure 1 illustrates the physical layout of the system consisting of the servo motor control mechanisms of the antenna azimuth system, which relies on reference and feedback signals from two potentiometers[7]. Researchers have examined various control techniques to effectively address the challenge of positioning antenna azimuth systems.

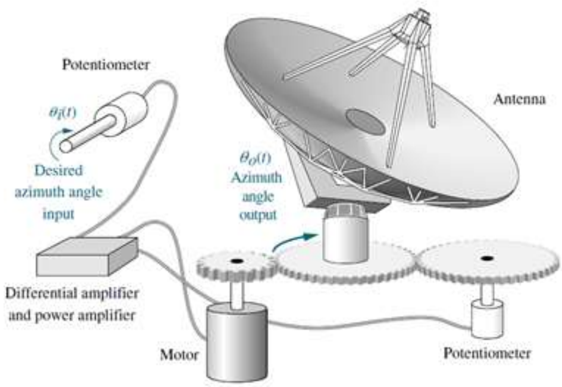

Figure 1. Layout of the antenna system

Rasheed et al.[8] have used the arc tan function of error to improve the PID controller for antenna azimuth position. The PID parameters were tuned by using Particle Swarm Optimization (PSO) based on root Mean Square Error, While Eze et al. [9] and Kumar et al. [10] have added a compensator with a PID and PI controller loop to the robustness of the parabolic antenna position control by minimizing steady-state error and settling time. Another method has applied to two controllers adjusting the orientation of the antenna, as suggested by Uthman and Sudin [11]. Both State-feedback controller and PID controller were implemented with pole placement, state-space equation, as well as Ziegler-Nichols for tuning PID parameters. On the other hand, Chishti et al. [12] has compared the response of antenna azimuth position control using PID and LQR controllers, whereas the linear quadratic regulator controller has more stability than the PID controller.

According to Akwukwaegbu et al [13], an MFC-PID control technique utilizing Model Following Control has been developed to enhance the stability of the azimuth position while minimizing position error. This technique has proven to be more effective than the traditional PID technique in terms of settling time and overshooting. Herdiana and Gunawan [14] have successfully tackled the challenge of accurately tracking satellite orbit positions while maintaining signal strength and reducing signal attenuation. They achieved this by utilizing a Field observation method to gather information data based on factors such as satellite type, frequency allocation, and signal strength of the satellite's trajectory as well as, they presented a quantitative empirical descriptive method was used for the mathematical approach. While Ahlawat et al. [15] introduced Model Predictive Control to stabilize the position of the antenna and achieve the strongest signal communication possible. They have been observed that the MPC time response with external disturbances significantly reduces azimuth angular error when compared to the PID controller.

Several studies with different control methods have been adopted by researchers. Singh and Pal [16], including adaptive controllers and self-tuning controllers, which are capable of handling external disturbances and minimizing deviation from the desired azimuth angle. In terms of fast time response with minimum overshoot, the self-tuning controller has displayed superior system response compared to the proposed model reference adaptive controller regarding the various of plant parameters. According to maintain stable system performance, Sahoo and Roy [17] have incorporated the quantitative feedback technique while considering uncertainties in the azimuth position.

From the other researcher’s point of view, fuzzy logic control has been proposed. Yakubu et al. [18] applied a fuzzy logic control that adjusts the precise antenna position without overshooting to ensure a reduction in the steady-state error and a decrease in the rising time. Furthermore, Okumus et al. [19] tested a fuzzy logic controller that had various membership functions and different types of rules. They found that the FLC triangular membership and 3x3 rule had the best response and better than the classical PID. Moreover, they examined the self-tuning of FLC, which showed the best performance over the PID and FLC controllers regarding the time response curve [20.[

This paper investigates the application of fuzzy logic controllers in controlling the orientation of an antenna. Regarding the time response curve performance and flexible adaptability, three different control systems are proposed and discussed: basic fuzzy PD logic control system (FPD), fuzzy logic control system with an I controller (FPDI), and fuzzy logic control system plus an I controller (FPD+I). the behaviors evaluation of proposed FLC controllers are implemented using MATLAB Simulink tools according to the following tests: (a) constant input without external disturbance, (b) multi-level input without external disturbance, and (c) multi-level input with external disturbance.

The structure of this paper is organized as follows: The introduction in Section 1. The methodology is described in section 2, which includes the mathematical expression and the transfer function of the antenna azimuth model, as well as the design of fuzzy logic control systems. In Section 3, the results and discussion, which includes the three proposed controllers using MATLAB simulation. Finally, Section 4 concludes the optimal results of the proposed controllers.

2. Case and Methodology

2.1. Antenna Azimuth model

The system includes two potentiometers for controlling the azimuth position, as shown in Figure 1. One potentiometer is used to manually adjust the antenna angle, while the other is used as a transducer to obtain the actual position of the antenna in the system. The differential amplifier calculates the error signal based on the difference between the input and output voltage of the potentiometer signals, and a power amplifier is used to increase the peak of the control signal to achieve the desired voltage value that drives the motor via a gear system. Figures 2 and 3 depict the schematic and block diagram of the azimuth control system respectively[7].

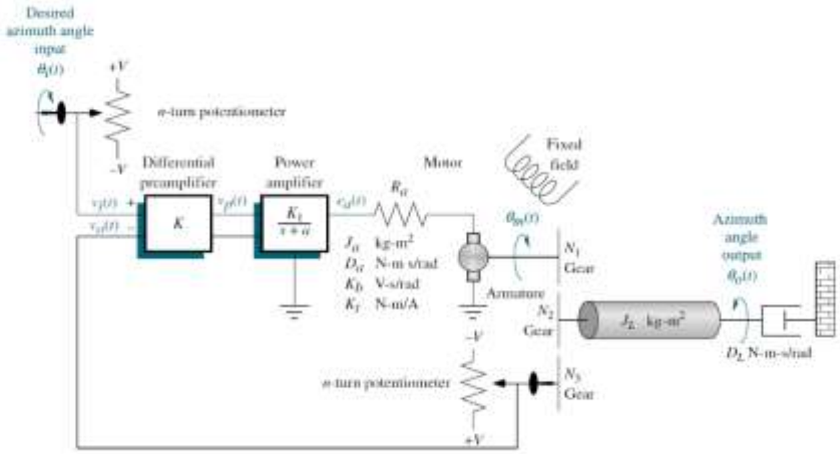

Figure 2. Schematic diagram of the antenna system

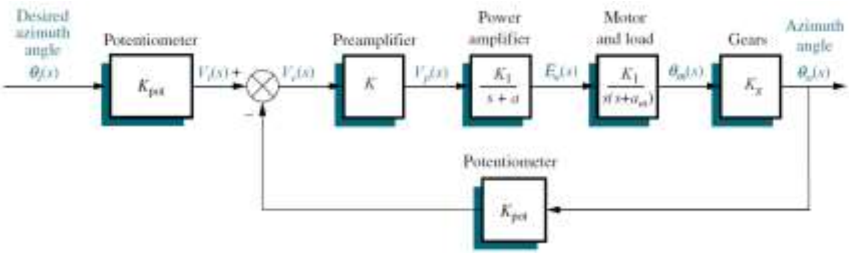

Figure 3. Block diagram of the antenna system

In terms of calculating the transfer function of the motor with the load effect, the equivalent equations of the overall inertial and dampening components have been used with the substitution of the motor and load poles and zeros (equations 1-4) to obtain the simplified equation given in equation (5)[7].

$$K_m = \frac{K_t}{J\,R_a} \quad (1)$$

$$a_m = \frac{D_m R_a + K_b K_t}{J R_a} \quad (2)$$

$$J = J_a + J_L (K_g)^2 \quad (3)$$

$$D_m = D_a + D_L(K_g)^2 \quad (4)$$

$$\frac{\Phi_m(s)}{E_a(s)} = \frac{K_m}{s(s+a_m)} \quad (5)$$

The gear ratio, Kg, can be calculated using equation (6) as follows:

$$K_g = \frac{N_1}{N_2} \quad (6)$$

According to finding the final close loop transfer function of the antenna's azimuth position, the schematic parameters values in Table 1 have been used.

Table 1. Schematic and block diagram parameters [7]

Parameters	Definition	Values
V	Output voltage of potentiometer [V]	10
n	Potentiometer turns	10
K_1	Gain of power amplifier	100
a	Pole of power amplifier	100
R_a	Resistance of motor [ohms]	8
J_a	Inertial constant of motor [kg-m2]	0.02
D_a	Damping constant of motor [N-m s/rad]	0.01
K_b	Back EMF [V-s/rad]	0.5
K_t	Torque constant of motor [N-m/A]	0.5
N_1, N_2, N_3	Gear teeth	25,250,250
J_L	Load inertial constant [kg-m2]	1
D_L	Load inertial constant [N-m s/rad]	1
K_{pot}	Potentiometer gain	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

Therefore, the transfer function of the overall system is given by equation (7).

$$\frac{\theta_o(s)}{\theta_i(s)} = \frac{318}{s^3+101.7s^2+171\,s+318} \qquad (7)$$

2.2 Fuzzy logic control design

The antenna's azimuth position can now be controlled using a fuzzy logic controller. In the world of antenna azimuth position control, where precision and adaptability are paramount, a range of control methods have been developed to ensure optimal performance. Having the use of fuzzy controllers, fuzzy-integral controllers, they could be a powerful tool in controlling antenna azimuth positions with the desired degree of accuracy and flexibility. In this section, we will delve into these controllers, explore their principles, and discuss their applications in the context of antenna systems, with a focus on their suitability for telescope applications. Fuzzy logic's ability to handle imprecise data, incorporate human expertise, and adapt to changing conditions makes it a valuable choice for maintaining the precise positioning required in antenna systems, especially in telescope applications where high levels of precision are critical. The design of the fuzzy controller comprises three main sections: fuzzification, interferential mechanism, and defuzzification[21], [22]. Table 2 shows the linguistic rule base that has been used for the design of the fuzzy logic controller that will be used in the three controllers, FPD controller, FPDI controller, FPD+I controller. Both inputs (PE and CE) and the output (U) have seven memberships which are:

- Negative big (NB)
- Negative medium (NM)
- Negative small (NS)
- Zero (Z)
- Positive small (PS)
- Positive medium (PM)
- Positive big (PB)

Table 2. Fuzzy rules

PE \ CE	NB	NM	NS	ZR	PS	PM	PB
NB	NB	NB	NB	NB	NS	Z	PS
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

Fuzzy inference is a method used to determine the fuzzy characteristics of the output, considering the impact of every rule in the rule base, after creating the fuzzy input. Afterwards, the fuzzy output is transformed into a crisp control signal through a process called defuzzification. Figure 4 illustrates the membership functions of the proportional error signal, variation of the error, and the output control signal. Trapezoidal functions are employed at both ends of the input and output variables to cover all the extremes range of values along with multiple gaussian functions in between to ensure smooth change in the degree of the membership for variable change [23]–[25].

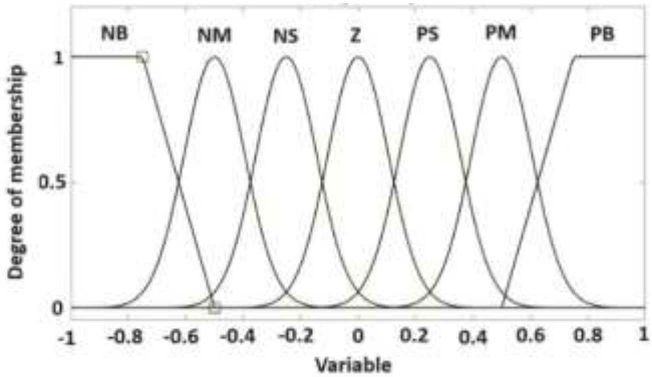

Figure 4. Input and output membership functions

The structure of a standard fuzzy has been employed in which the controller has two inputs, proportional error (PE) and change in error (CE) with a single controller output (U) [26], [27]. After designing the fuzzy controller, it will be used in the three controllers. Firstly, it will be used without adding the integral part. The design process will also involve the choice of the KE1, KCE1 and KU1. Secondly, it will be used with the FPDI controller. This controller will have the same fuzzy controller, but it has an integral part connected in cascade with it. Same as the fuzzy controller, the design will involve the choice of the KE2, KCE2 and KU2. Finally, it will be used in the design of the fuzzy FPD+I controller where the integral part will be added in parallel with the fuzzy controller. Same as the fuzzy controller, the design will involve the choice of the KE3, KCE3 and KU3. Figure 5 shows the block diagram of the Simulated close loop block diagram of the system with the three designed controllers.

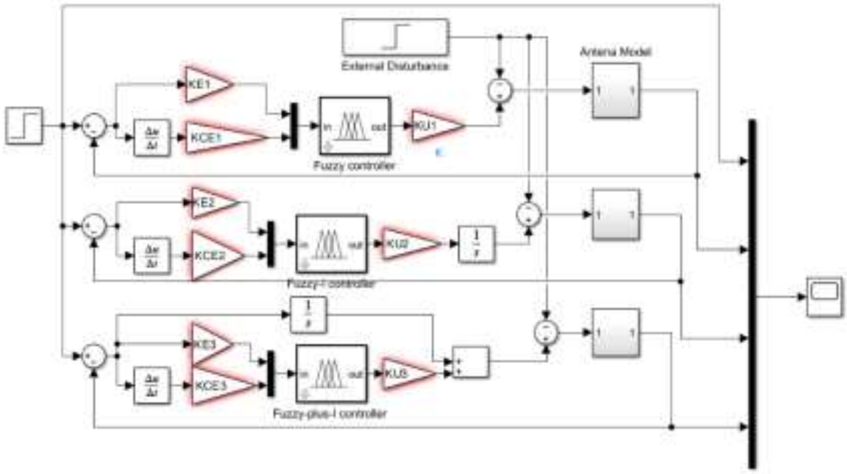

Figure 5. Block diagram of the system with the three controllers

The process of manually tuning involves calculating the controller gains (KE, KCE, and KU) for optimal performance. This is achieved through multiple simulations with varying gains in specific regions as shown in Table 3. So, the most appropriate gain values can be determined by analyzing the system's response.

Table 3. Gain values of the controllers

Controller gain (Fuzzy PD)	Value	Controller gain (Fuzzy PD-I)	Value	Controller gain (Fuzzy-plus-I)	Value
KE1	1.8	KE2	2.1	KE3	1
KCE1	1	KCE2	1	KCE3	1
KU1	25	KU2	0.52	KU3	45

3. Results and Discussion

In this section, the performance of the three controllers has been compared while evaluating the response of them after many experiments. These experiments have been divided into three scenarios to evaluate the response of the system in terms of the transient and steady state responses.

3.1 First test: Constant test input without external disturbance

In this test, the input will be is a unit step initiated at t=1 second and the response of the system will be analyzed according to it. Figure 6 shows the response of the three controllers where the response of the three controllers can be compared. It is noticed that the FPD controller has a steady-state error even though it has the fastest response. At the same time, FPDI being the slowest in response even though both FPDI and FPD+I controllers were able to diminish the steady-state error.

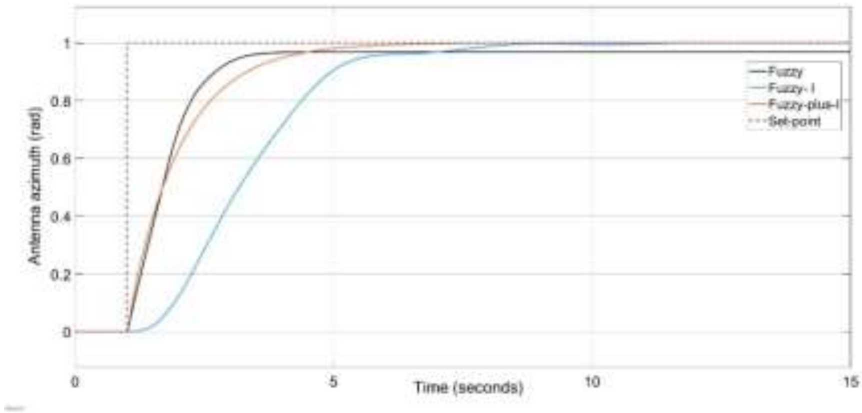

Figure 6. Step response of the FPD, FPDI and FPD+I Controllers

To provide more details regarding the response of the controllers, Table 4 has the time response specifications.

Table 4. Time response specifications

Controller	%OS	Tr (sec)	Ts (sec)	Ess
Fuzzy PD	0	1.90	3.21	0.0316
Fuzzy PD-I	0	3.00	7.60	0
Fuzzy plus I	0	2.22	5.00	0

To further evaluate the controllers, an alternative method that involves analyzing the error signals has been presented as shown in Figure 7. Upon analysis, it is apparent that the FPD achieves the quickest reduction in error when compared to other controllers. However, it is important to note that even though it performs well, it was unable to eliminate the error, falling short of reducing it to zero.

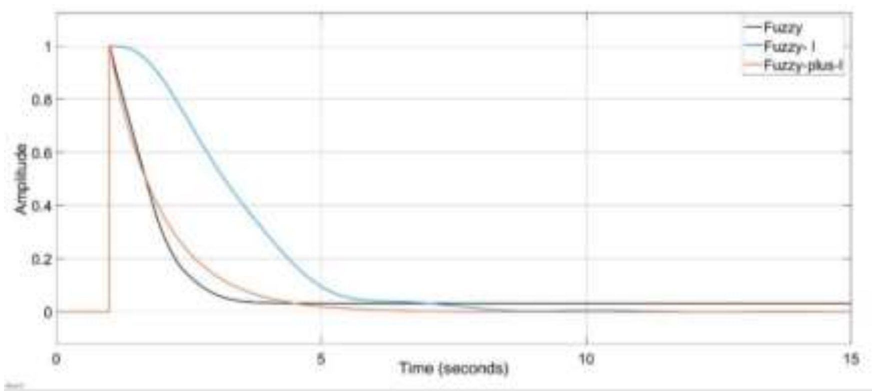

Figure 7. Error signals for the step response

It is essential to examine the control signal of each controller to monitor how their profiles change with every input modification as in Figure 8. The FPD demonstrates a unique feature with a sharp rise in the control signal as soon as the input transitions from 0 to 1. The signal reaches a peak of 19.95, and another minor ripple at t=2 seconds, it maintains a smooth profile with a value of 0.969. In contrast, the FPDI controller has a gradual change in the control signal, taking 8.2 seconds to reach its final value of one. Lastly, the FPD+I controller exhibits a control signal profile similar to the fuzzy controller, peaking at 35.9, with minor ripples occurring at 1.5 seconds and 2 seconds.

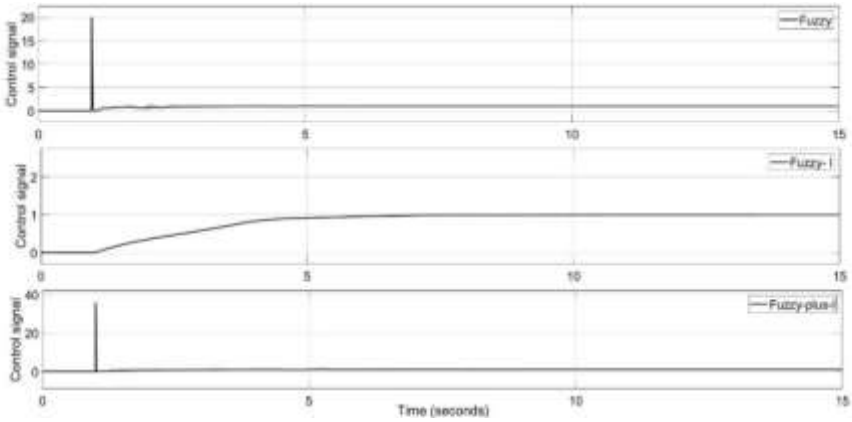

Figure 8. Control signals

3.2 Second test: Multi-level test input without external disturbance

In the context of this examination, the input signal is comprised of a unit step response that is initiated at t=1 second, immediately followed by a substantial step increase in the signal level to 2 at t=15. This step increase is sustained for a period until the signal level returns to its initial value of 1 at t=30. The entire input signal profile is well illustrated and depicted in Figure 9.

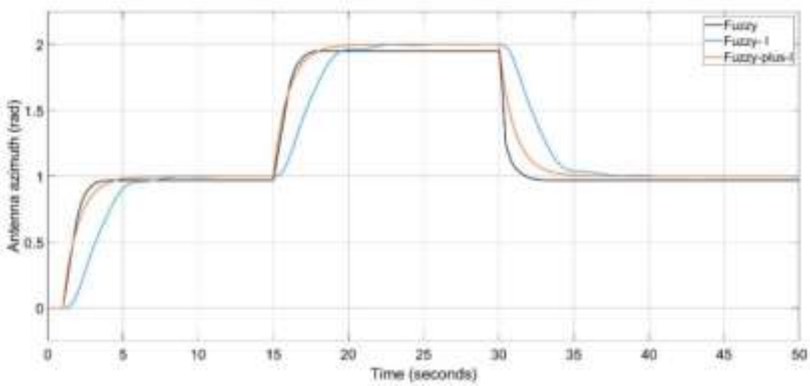

Figure 9. Step response of the FPD, FPDI and FPD+I Controllers

It is essential to observe the response of the controller to both step-up and step-down changes during the examination. The FPDI and FPD+I controllers behave similarly to t=1 second during the step-up change at t=30 seconds. In contrast, the FPD controller accumulates the steady-state error of 0.0632. During the step-down change, all three controllers exhibit the same responses. To compare the error signals easily, the differences between them are shown in Figure 10.

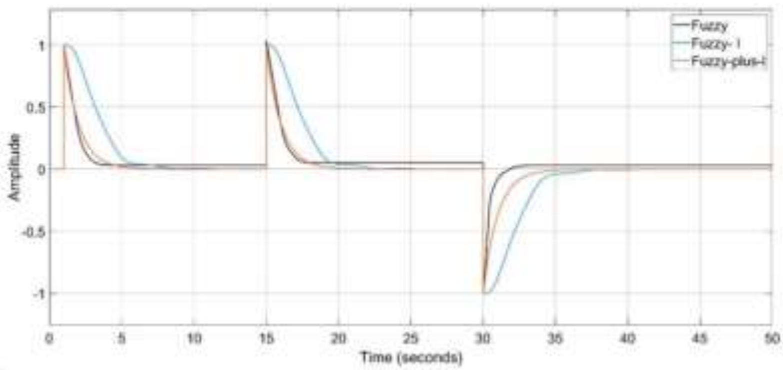

Figure 10. Error signals for the step response

To examine the control signals of the three controllers shown in Figure 11, it becomes apparent that the control signals maintain a comparable profile to that seen in Figure 8. Notably, after the step-down change at t=30.5, the FPD controller experiences a sudden rise with a contrary sign. It is crucial to acknowledge that this discrepancy in the fuzzy controller's control signal could have substantial consequences for the overall system's operation and warrants further investigation.

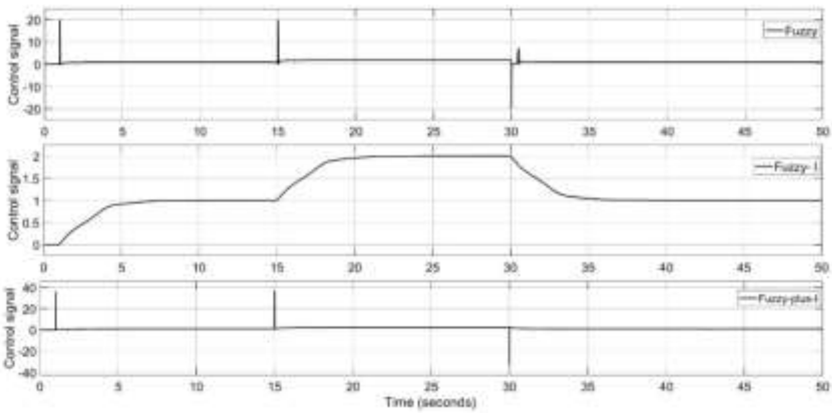

Figure 11. Control signals

3.3 Third test: Multi-level test input with external disturbance

As the proposed system does not work in an ideal environment, many external disturbances could affect its performance such as mechanical vibrations, atmospheric turbulence, electromagnetic interference (EMI), and thermal variations, the final assessment holds paramount importance as it introduces an external disturbance to evaluate the controller's robustness. Figure 12 illustrates the step response of the three controllers. It is crucial to observe the controller's behavior at t=30 seconds when the disturbance is introduced. Regarding the FPD controller, attempts were made to align the actual azimuth with the desired azimuth. However, the steady-state error increased from 0.0316 to 0.059. In the case of the FPDI controller, it exhibited the onset of two periodic oscillations with a 2% overshoot. Conversely, the FPD+I controller adeptly managed the disturbance, showcasing a flawless response.

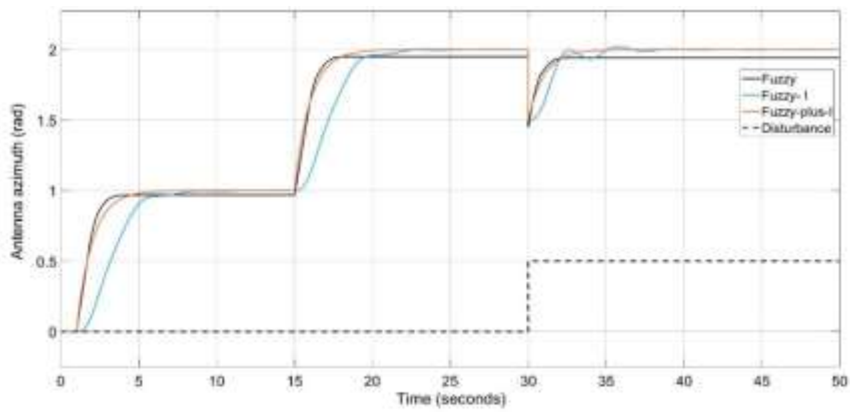

Figure 12. Step response of the FPD, FPDI and FPD+I Controllers

The error signals for this test shown in Figure 13 have the same profile as the previous tests except that it has additional part at t=30 seconds for the disturbance rejection.

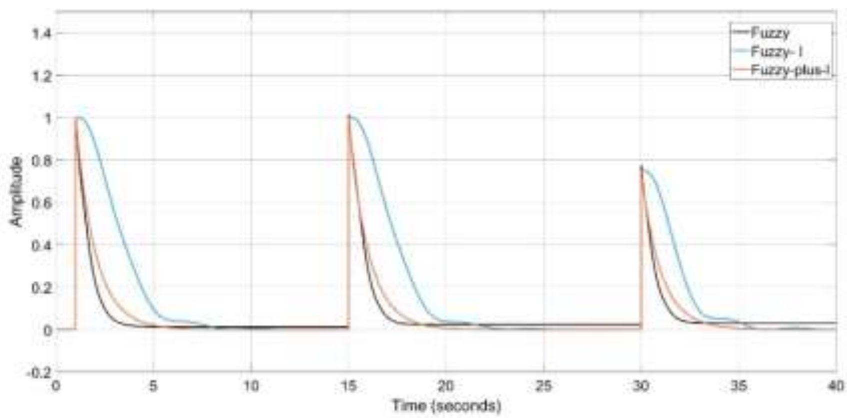

Figure 13. Error signals for the step response

Finally, the control signals for this test are shown in Figure 14.

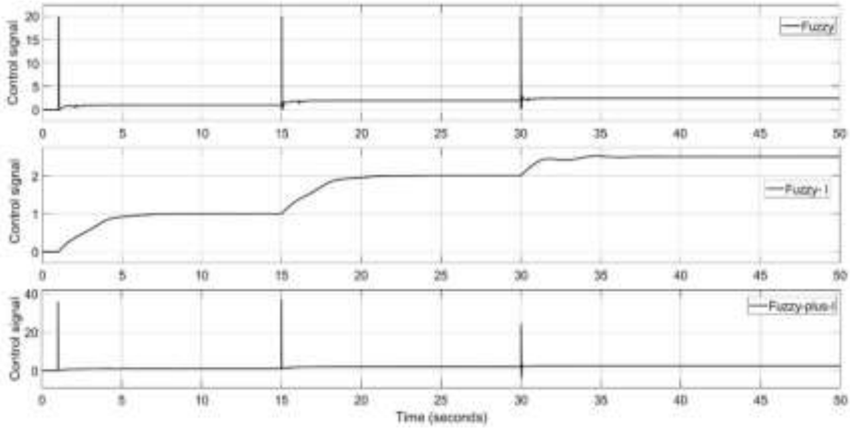

Figure 14. Control signals

To sum up, although the FPD controller has the fastest response, FPD+I controller is the best controller because it is faster than the FPDI controller and does not have a steady state error as the FPD control does. The steady state error is the most important parameter because the azimuth of the antenna must be controlled with zero- steady state error.

4. Conclusions

Based on extensive research, it has been determined that the optimal method for controlling the azimuth of an antenna is through the use of a FPD+I controller. To make this determination, the performance of three controllers was compared: the FPD controller, the FPDI controller, and the FPD+I controller. Although the FPD controller displayed the quickest response, it had a steady-state error that increased when an external disturbance was present. On the other hand, both the FPDI and FPD+I controllers were successful in eliminating steady-state error. However, when it came to speed and the ability to handle external disturbances, the FPD+I controller outperformed the FPDI controller. The FPDI controller displayed two periodic oscillators when an external disturbance was introduced. Overall, the findings of this research indicate that the FPD+I controller is the most effective choice for controlling the azimuth of an antenna. Its ability to mitigate steady-state error and handle external disturbances make it the superior option. This research provides valuable insights into controller performance that can be utilized in future studies in this field.

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