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Enhanced Hybrid Robust Fuzzy-PID Controller for Precise Trajectory Tracking Electro-Hydraulic Actuator System

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ABSTRACT

The Electro-Hydraulic Actuator (EHA) system integrates electrical and hydraulic elements, enabling it to generate a rapid reaction, a high power-to-weight ratio, and significant stiffness. Nevertheless, EHA systems demonstrate non-linear characteristics and modeling uncertainties, such as friction and parametric uncertainty. Designing a controller for accurate trajectory tracking is greatly challenging due to these limitations. This paper introduces a hybrid robust fuzzy proportional-integral-derivative (HFPID) and (HF+PID) controller. The controller is designed to effectively control a third-order model of an EHA system for trajectory tracking. It is a significant contribution to the development of an intelligent robust controller that can perform well in different environments. Initially, a mathematical model for the EHA system was created using a first-principle approach. Subsequently, the Ziegler-Nichols method was employed to fine-tune the PID controller, while a conventional Fuzzy Logic Controller (FLC) was constructed in MATLAB Simulink utilizing linguistic variables and rule-based control. Without further tuning, the FL and PID controller are combined as a hybrid controller with different structures: Hybrid Fuzzy-PID (HFPID) and Hybrid Fuzzy+PID (HF+PID) controller. The Mean Square Error (MSE) and Root Mean Square Error (RMSE) are utilized as indices to assess the tracking accuracy and robustness of the four controllers. A greater value of MSE and RMSE indicates poorer performance of the controller. The results demonstrate that the HF+PID controller surpasses the other controllers by reaching the lowest MSE and RMSE values. It showcases the efficacy and accuracy in monitoring sinusoidal, multi-sinusoidal, and point-to-point trajectory tracking. Future work should focus on implementing the designed controller on hardware for real-time performance and experimenting with various types of FLC or Hybrid controllers, such as self-tuning fuzzy-PID, to further explore their potential.

1. Introduction

Electro-Hydraulic Actuator (EHA), first introduced by French scientist Blaise Pascal in 1663 and emerged from the early 20th century advancements in fluid power technology [1]. EHA systems combine electrical and hydraulic systems [2]. The conventional EHA system consists of a pump, control valve, and hydraulic actuator, which provide linear motion [3]-[9]. They control the pressurized fluid flow from the motor pump to the electro-hydraulic control valve through an electrical signal, which is then transferred to the hydraulic actuator to generate precise trajectory. They are used in various sectors such as cranes, excavators, aviation [10]-[14], automotive systems, and industrial processes [15]-[18]. EHA systems are recognized for their impressive power-to-weight ratio, rapid response times, high accuracy [19], [13] and ability to transmit high pressures over long distances [20]-[24].

The EHA system can be made more responsive with advanced control techniques. Modelling and control are the most crucial procedures in engineering design. However, the inherent uncertainties, high nonlinearity, and time-varying characteristics [24]-[29] of the system make it challenging to construct a dynamic model and design a controller effectively. The EHA system relies on sensors to monitor system parameters, but the presence of nonlinearities and disturbances can affect its ability to accurately follow a desired trajectory [30]-[35]. Moreover, the customized controller settings further contribute to this behavior. Therefore, it is essential to develop a robust controller for different trajectory tracking in order to achieve outstanding precision, efficiency and to evaluate the robustness performance under different condition.

There are few existing control strategies that have been employed by past research including linear [36]-[48], intelligent [49]-[59] and hybrid control [60]. It involves analyzing system behaviors in different conditions and designing control inputs to maintain consistent performance. This research contribution aims to develop a robust hybrid controller that is capable of tracking diverse trajectories and assess its effectiveness across different environment conditions.

The linear control approach is widely adopted and considered the simplest control method for system implementation. The system reaction to varied inputs is commonly characterized by a set of linear differential equations [35]-[40]. These strategies continue to be widely employed in the industry to this day [41]-[43]. The use of Ziegler-Nichols method is proposed in [44]-[48] as a means of controlling the position of the actuator in the EHA system. The PID control technique is a popular alternative to linear control methods for tracking control in EHA systems. It is widely used in industrial control systems due to its simple design and execution. PID control is used to evaluate tracking performance compared to other control systems. Furthermore, in order to get the best possible performance in tracking the desired trajectory using PID control, it is necessary to do extensive exploration to determine the optimal values for the control variables.

Next, intelligent control is a method that employs several AI techniques to create controllers capable of adjusting to dynamic conditions and enhancing the performance of the system being controlled. The typically employed techniques in intelligent control include Artificial Neural Networks (ANN) [58] and Fuzzy Logic Control (FLC) [49]-[57]. A FLC method is suggested in [50] to regulate the EHA system by specifically addressing the challenges provided by load fluctuations which can lead to oscillation behavior.

Furthermore, hybrid control strategies involve combining or integrating several control techniques or approaches to produce better system performance, robustness, and efficiency compared to using a single control method. A hybrid FLC combined with PID controller is as a solution to address the nonlinearities and uncertainties present in the EHA system. In addition, a Hybrid Fuzzy PID (HFPID) controller is developed for the purpose of regulating the cylinder position in the EHA system. The Hybrid Fuzzy Fractional Order-PID control approach is introduced in [48] for the EHA system, considering changes in operating conditions. In [55], a novel approach is shown for tuning an online fuzzy system combined with an online modified-grey predictor. This method is specifically designed for uncertain nonlinear EHA systems.

Robust control is crucial for ensuring EHA system stability and performance in the presence of uncertainties and disturbances. Linear control methods are commonly used due to their simplicity in handling the dynamic behavior of EHA systems [21], [22]. However, their adoption is limited as they often fail to meet the performance requirements of modern EHA systems [24], [25]. Intelligent control strategies, on the other hand, offer adaptability to dynamic conditions but typically involve complex algorithms and rely heavily on human expertise. Hybrid control techniques such as Hybrid Fuzzy-PID, combine the advantages of both linear and intelligent control that offer high-precision trajectory tracking and robustness with a reliance on human intelligence [56]. HFPID and HF+PID offer benefits such as improved tracking accuracy, greater resilience to parameter fluctuations, and more adaptability in dynamic and uncertain contexts. HF+PID approaches have the capacity to enhance the tracking performance, resilience, and adaptability of systems, making them a practical choice for attaining optimal control in EHA applications that will contribute to this research.

2. Methodology

2.1. Research Methodology Flowchart

This section outlines the research process conducted on the EHA system, represented through a flow chart divided into three parts, each reflecting the research objectives. The first phase involves deriving the mathematical model using first principles. In the second phase, the developed mathematical model of the EHA system is employed to design an intelligent robust controller for trajectory tracking. Finally, the third phase focuses on evaluating the robustness of the controller design under various environment conditions.

Fig. 1 shows flowchart of the research. This research commences with the development of a dynamic model of the EHA system using first principles, resulting in a comprehensive mathematical model. Subsequently, a PID controller is designed utilizing the Ziegler-Nichols method, and simulations are conducted in MATLAB Simulink. Following the tuning of the PID controller, a Fuzzy Logic Controller (FLC) is designed, with both the conventional PID and FLC controllers being validated through sinusoidal, multi-sinusoidal, and point-to-point trajectory tracking. Given the limitations identified in previous studies, this research contributes by developing a Hybrid Fuzzy-PID controller with two different configurations. Finally, the tracking performance and robustness of the Hybrid Fuzzy-PID controller are analyzed.

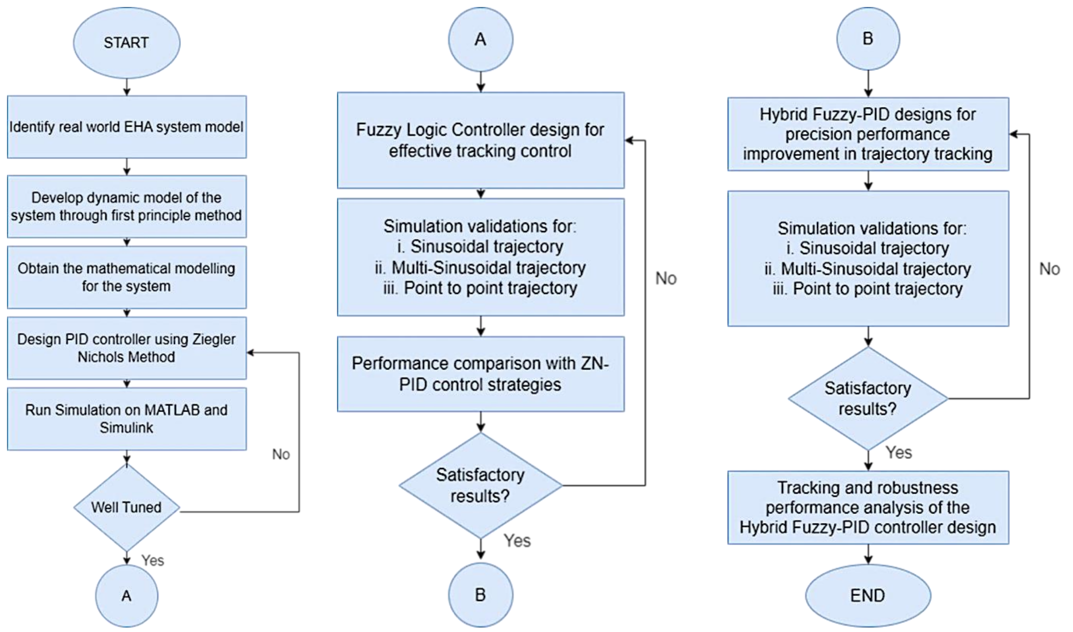

Fig. 1. Flowchart of the research methodology

2.2. Mathematical Modelling

The mathematical model of the EHA system has been developed using first principles, incorporating parameters such as mass, damping, and stiffness to accurately describe the entire system. Defining Q_L as movement of the cylinder and the leakage oil flow, this factor represented in (1) where $V_t, A_p, \dot{x}_p, \beta_e$ and $f(P_L)$ are the total compressed oil volume, cylinder piston surface area, cylinder piston velocity, effective bulk modulus coefficient and the nonlinear function of internal and external oil leakage, respectively. Equation (1) represents the relationship that describes the overall oil flow dynamics of the EHA system, derived through a series of linearizations. Equation (3) delineates the force produced by the actuator, which results from the total mass acting on the piston.

$$Q_L = A_P\dot{x}_p + \frac{V_t}{4\beta_e} + f(P_L) \tag{1}$$

$$F_a = A_P\, P_L = M_t\ddot{x}_p \tag{2}$$

Equation (3) represent the combination of (1) and (2), a complete mathematical model for EHA system is constructed in form of transfer function.

$$\frac{M_t\ddot{x}_p}{A_P} = \frac{4\beta_e}{V_t}\left(K_q u - \left(K_c + C_{tp}\right)\frac{M_t\ddot{x}_p}{A_P} - A_P\dot{x}_p\right) \tag{3}$$

The differential equation in (3) undergoes a Laplace transform, yielding the transfer function of the EHA system model, represented as equation (4). Here, $X_p(s)$ denotes the displacement position of the hydraulic cylinder and U(s) represents the input voltage applied to the valve.

$$\frac{X_p(s)}{U(s)} = \frac{\frac{4\beta_e A_P}{M_t V_t}K_q}{s^3 + \frac{4\beta_e}{V_t}\left(K_c + C_{tp}\right)s^2 + A_p^2\frac{4\beta_e}{M_t V_t}s} \tag{4}$$

Table 1 presents the symbols and parameter values for the EHA system. These values are utilized in the design of the controller to accurately represent the behavior of the EHA system, given that the scope of this study is exclusively focused on simulation methods.

Table 1. Symbol and parameter value of EHA system

Parameter	Description	Values
A_p	Surface area of the position	0.0013
β_e	Effective bulk modulus	1.7×10^9
M_t	Total mass	9
V_t	Total oil volume	0.0026
C_{tp}	Total leakage coefficient	0
K_c	Flow-pressure coefficient	$1x10^{-15}$
K_q	Flow-gain coefficient	$1x10^{-15}$

2.3. Ziegler Nichols-PID

PID control, or proportional-integral-derivative control, is a common linear control technique. It is widely used in industrial control systems and other applications that require continuous modulation of control. This general feedback control loop mechanism employs a combination of three control terms - proportional, integral, and derivative to regulate the behavior of the system. The propose method for tuning of suitable parameter in this research, Ziegler Nichols is adopted for tuning the controller parameter as shows in Table 2. The ultimate gain K_{ult} is obtained from MATLAB and Simulink by adjusting the controller gain parameter, where only K_p value is increase until a sustained oscillation is obtained whereas the K_i and K_d stays zero. The ultimate period, T_{ult} is obtained after the oscillation is sustained. The parameter is obtained based on Table 2 where it will used in (5).

Table 2. PID parameters

Parameter	Equation
K_p	$\frac{K_{ult}}{1.7}$
T_i	$\frac{T_{ult}}{2}$
T_d	$\frac{T_{ult}}{8}$

$$G_{PID}(s) = K_p(1 + \frac{1}{T_i s} + T_d s) \quad (5)$$

2.4. Fuzzy Logic Controller

Next, the proposed method is to use Fuzzy Logic Controller (FLC) which the common technique for electro-hydraulic systems. FLC has emerged as a prominent method for effectively managing EHA systems due to its ability to handle uncertainty and nonlinearity. EHA systems are characterized by complex dynamics and inherent nonlinearities, which make traditional linear control techniques challenging to apply. FLC overcomes these challenges by using linguistic variables and flexible rule sets to model and control the system behavior. Fuzzy rule-base system can be created to reflect the expertise and knowledge of subject matter experts where it can be modified to maximize the system performance.

There is two inputs and one output for the FLC where the error and the rate change of the error of the system are the input while the voltage is the output of the system. The structure of FLC is shown in Fig. 2 while Fig. 3, Fig. 4 and Fig. 5 shows membership function of error, rate change of error and voltage respectively. The fuzzy logic rules are constructed in Table 3. There are 27 rules built for this FLC where the nine linguistic variables of the error and three linguistic variables of the rate change of error resulted in 27 rules based on the nine linguistic variables of the voltage output. The fuzzy rule was determined through a trial-and-error process. Voltage membership function shown in Fig. 6.

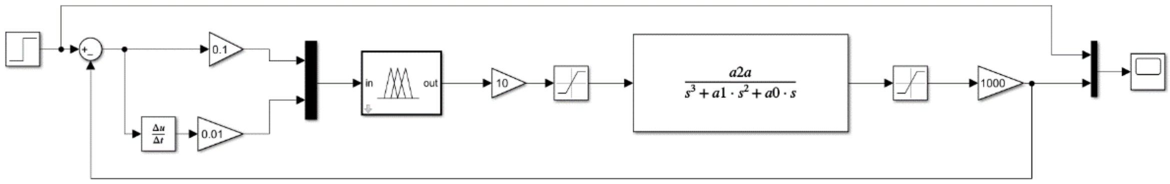

Fig. 2. Fuzzy logic controller

Table 3. Fuzzy rules

		Error, e								
		VLN	LN	SN	VSN	Z	VSP	SP	LP	VLP
Rate Change of Error, de/dt	N	VLN	VLN	LN	SN	VSN	Z	SP	SP	LP
	Z	VLN	LN	SN	VSN	Z	VSP	SP	LP	VLP
	P	LN	SN	VSN	Z	VSP	SP	LP	VLP	VLP

2.5. Hybrid Fuzzy PID Controller (HFPID)

The HFPID controller is a hybrid controller that combines the advantages of both FLC and PID controllers to successfully handle complicated and nonlinear control systems. This hybrid approach integrates the most favorable characteristics of fuzzy logic and control to attain higher control performance and improved system stability. By integrating fuzzy logic with PID control, the control system acquires the capability to efficiently modify and accommodate various operating situations. It grows increasingly adept at managing disruptions and ensuring stability. There are two types of hybrid methods. The first type involves a switching mechanism between FLC and PID by comparing the error with a predetermined threshold error that shows in Fig. 7 while shows in Fig. 8 is the second form is a combination of PID and FLC, where their outputs are summed together.

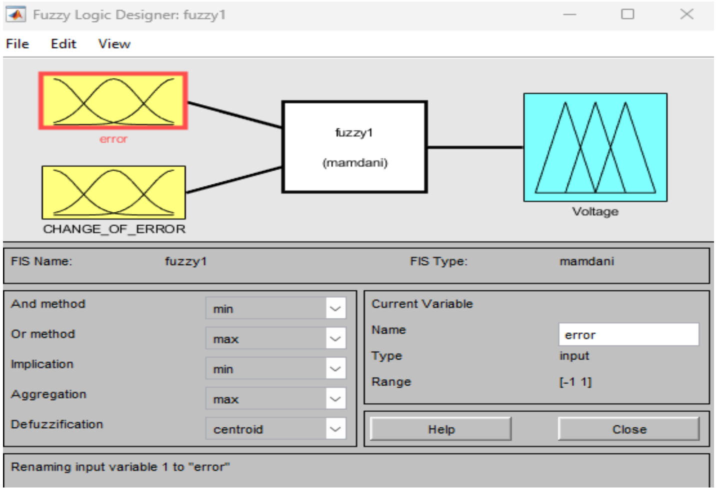

Fig. 3. Fuzzy logic toolbox

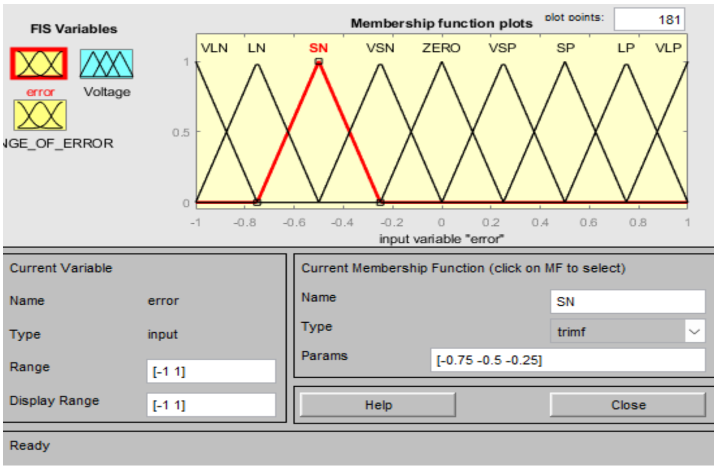

Fig. 4. Error membership function

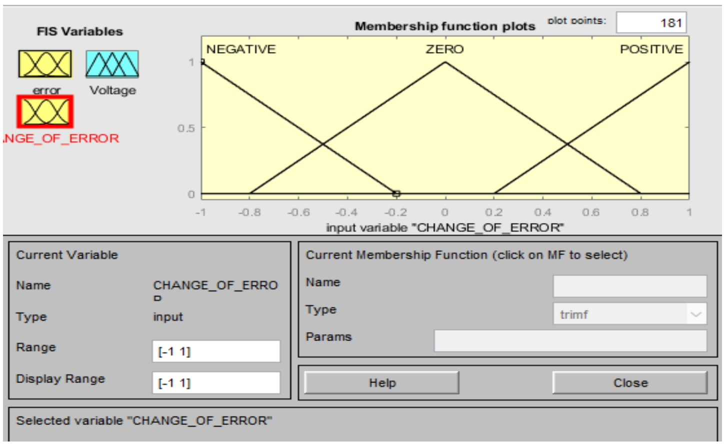

Fig. 5. Rate change of error membership function

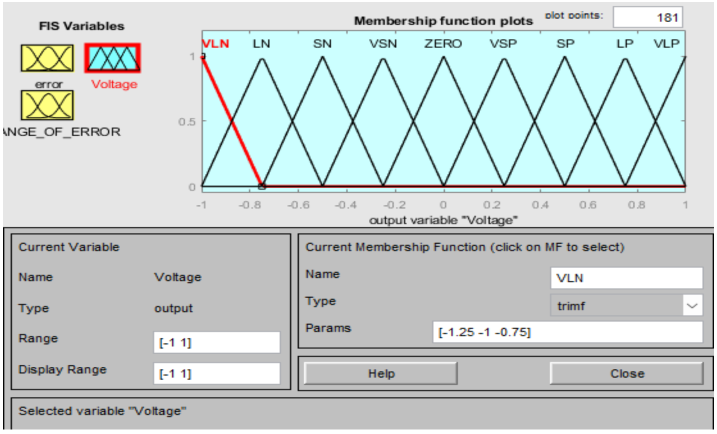

Fig. 6. Voltage membership function

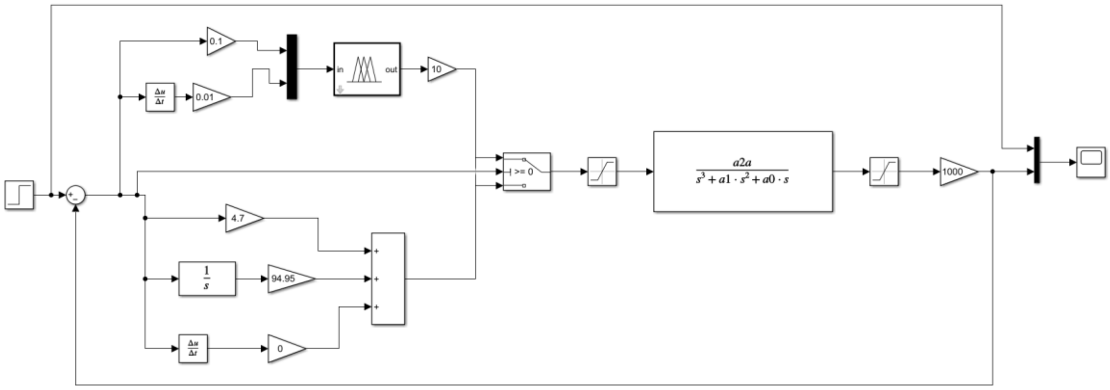

Fig. 7. Hybrid fuzzy PID controller structure

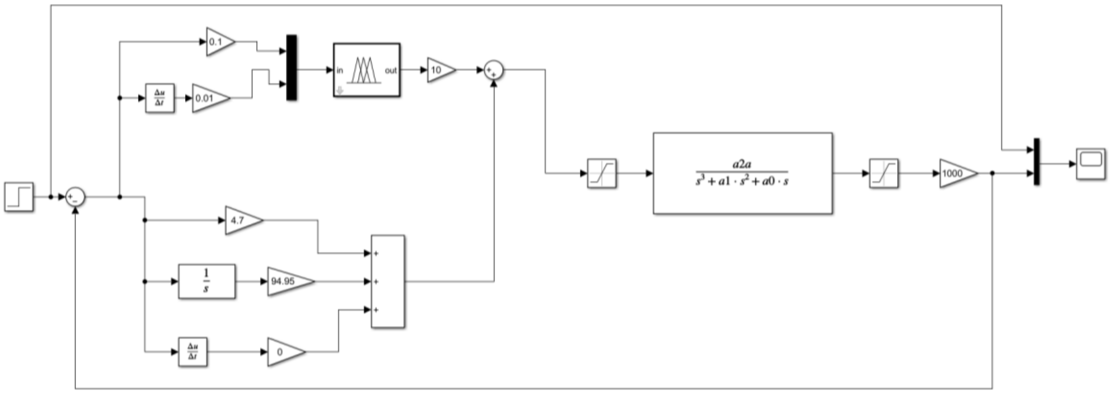

Fig. 8. Hybrid fuzzy + PID controller structure

2.6. Sinusoidal, Multi-Sinusoidal and Point-to-Point Trajectory

The trajectory refers to the desired direction or movement that a hydraulic actuator should follow in an EHA system. The most frequently seen trajectory types are sinusoidal and multi-sinusoidal trajectories. Implementing a sinusoidal trajectory in an electro-hydraulic system causes the actuator to produce smooth, oscillatory motion. Conversely, a multi-sinusoidal trajectory creates a motion pattern composed of multiple sinusoidal waveforms, each with distinct frequencies and amplitudes. These waveforms combine to generate a more complex trajectory pattern, often used in industrial automation, robotics, and motion control systems. The generation and control of these trajectory patterns within the electro-hydraulic system can be achieved using appropriate control algorithms and signal generation techniques.

The amplitude and frequency values used for sinusoidal trajectory tracking are 10 and 0.25 Hz, respectively as shown in Fig. 9. Additionally, three sinusoidal signals have been combined to produce a multiple sinusoidal trajectory shows in Fig. 10, each having an amplitude of 10 and frequencies of 0.25 Hz, 0.5 Hz, and 1 Hz. These two sorts of trajectories are utilized to observe the tracking position and resilience of the developed controller.

Furthermore, a point-to-point trajectory in Fig. 11 represents a specific method of moving the hydraulic actuator in EHA system. It involves commanding the actuator to travel directly from one predetermined position (starting point) to another designated position (end point). The essence of a point-to-point trajectory is its straight-line motion connecting the start and end positions. The actuator moves along the most direct path, ensuring efficiency and minimal deviation. The goal of using this trajectory is to reduce tracking errors and establish precise control over the actuator movement.

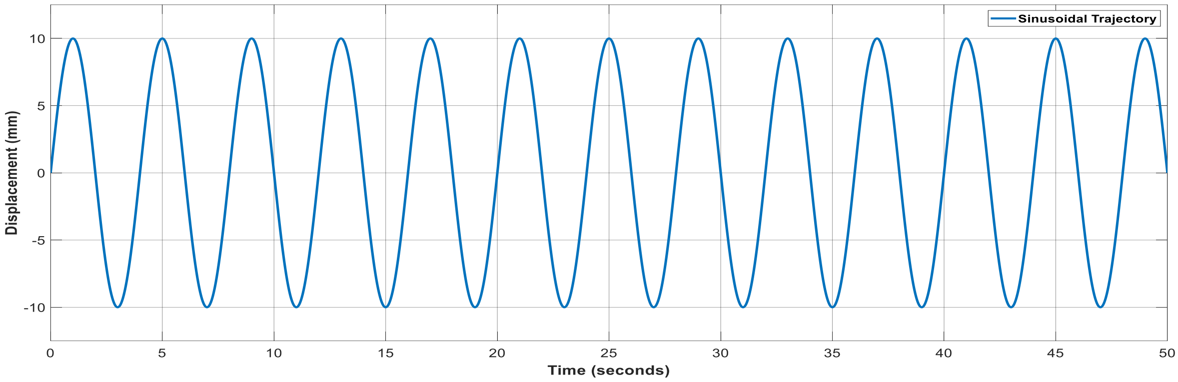

Fig. 9. Sinusoidal trajectory

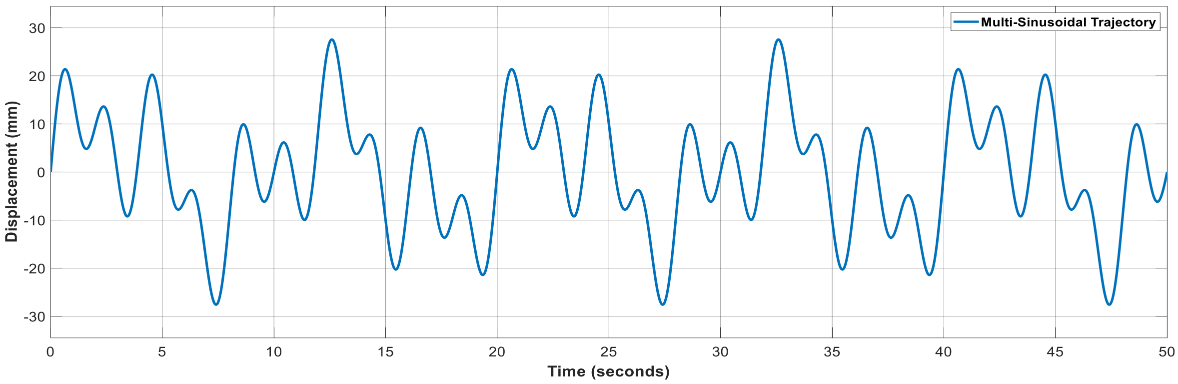

Fig. 10. Multi-sinusoidal trajectory

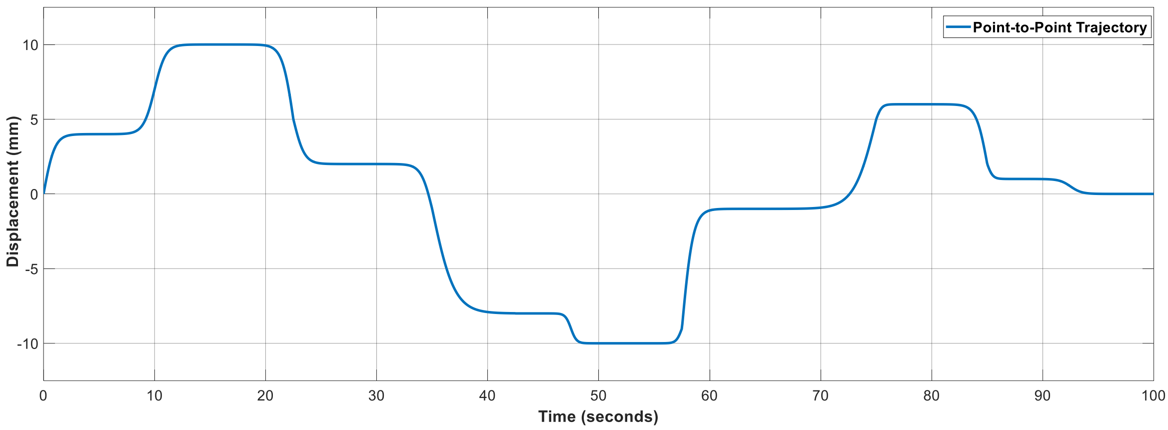

Fig. 11. Point-to-point trajectory

3. Results and Discussion

3.1. Sinusoidal Trajectory Tracking Responses

The designated four type of controllers has been analyzed in order to accurately simulate the trajectory tracking where sinusoidal as a reference. Fig. 12, Fig. 13, Fig. 14 and Fig. 15 shows the tracking performance of sinusoidal trajectory for ZN-PID, fuzzy logic, hybrid fuzzy PID and hybrid fuzzy + PID controller respectively. The overall tracking performance of sinusoidal trajectory has been tabulated where a detailed analysis of RMSE and MSE is conducted to evaluate the actual performance of the controllers.

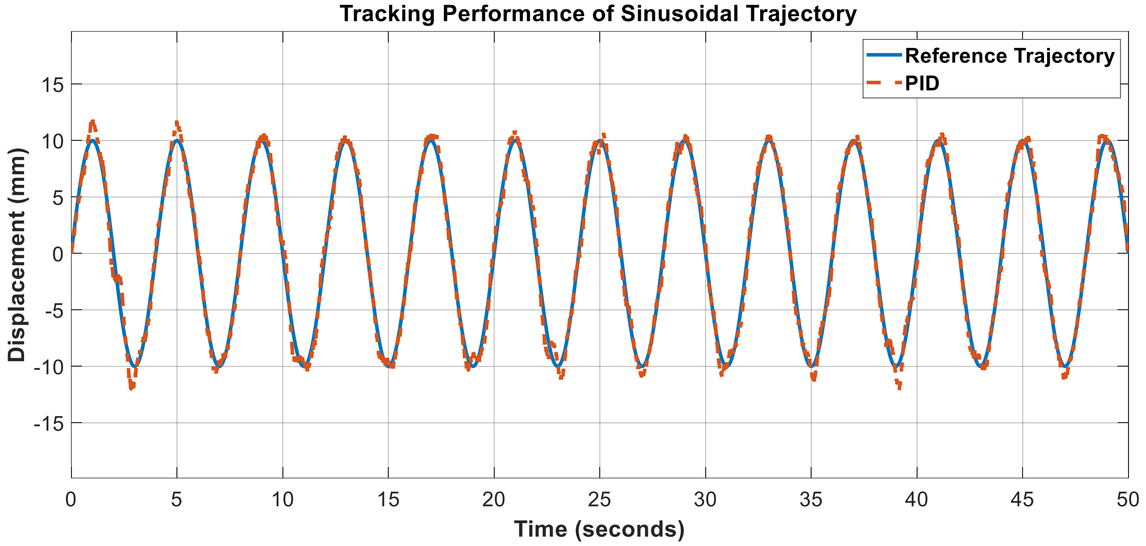

Fig. 12. Sinusoidal trajectory tracking response for ZN-PID controller

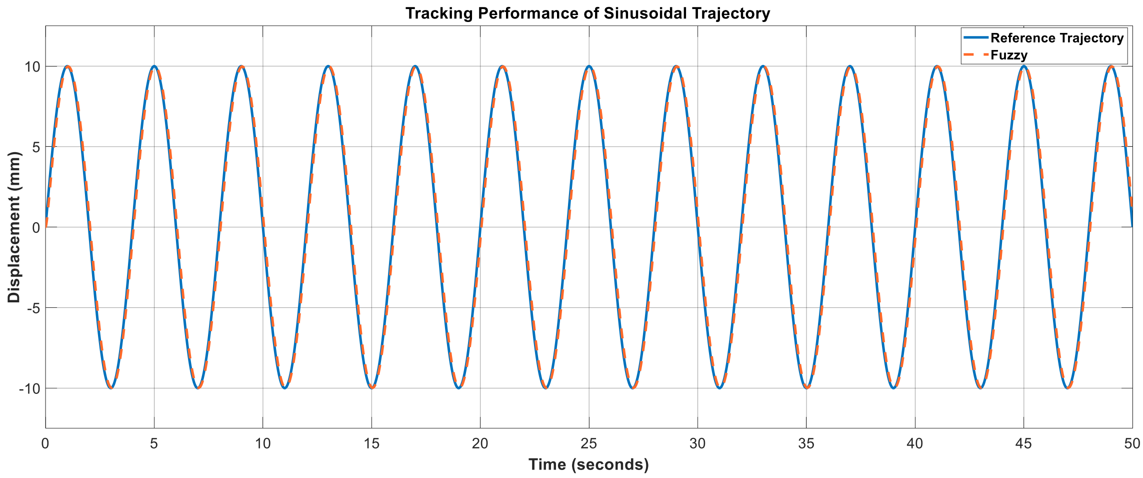

Fig. 13. Sinusoidal trajectory tracking response for fuzzy logic controller

Based on the Fig. 12, it is proof that the PID controller performs poorly, exhibiting a high ripple when attempting to follow the given trajectory signal. In contrast, both the Fuzzy Logic Controller (FLC) and the Hybrid Fuzzy-PID (HFPID) produce nearly identical tracking results, with the HFPID configuration indicating a strong dominance of the fuzzy controller. Ultimately, the HF+PID demonstrates the best tracking performance, closely following the trajectory signal with minimal ripple.

Table 4 shows that the ZN-PID controller has the greatest MSE and RMSE values compared to the other controllers. On the other hand, the HF+PID controller has the lowest MSE and RMSE values. Greater MSE and RMSE values imply a lesser level of precision in tracking the target trajectory.

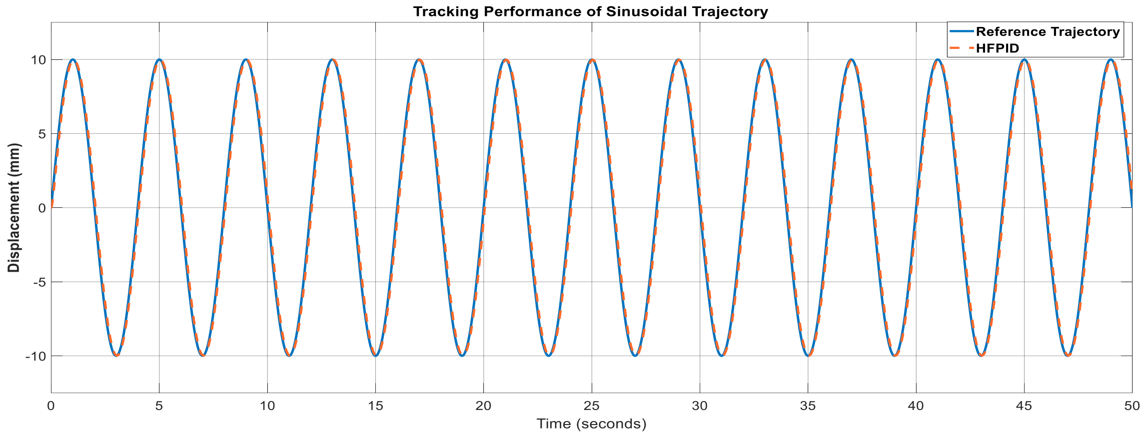

Fig. 14. Sinusoidal trajectory tracking response for hybrid fuzzy PID controller

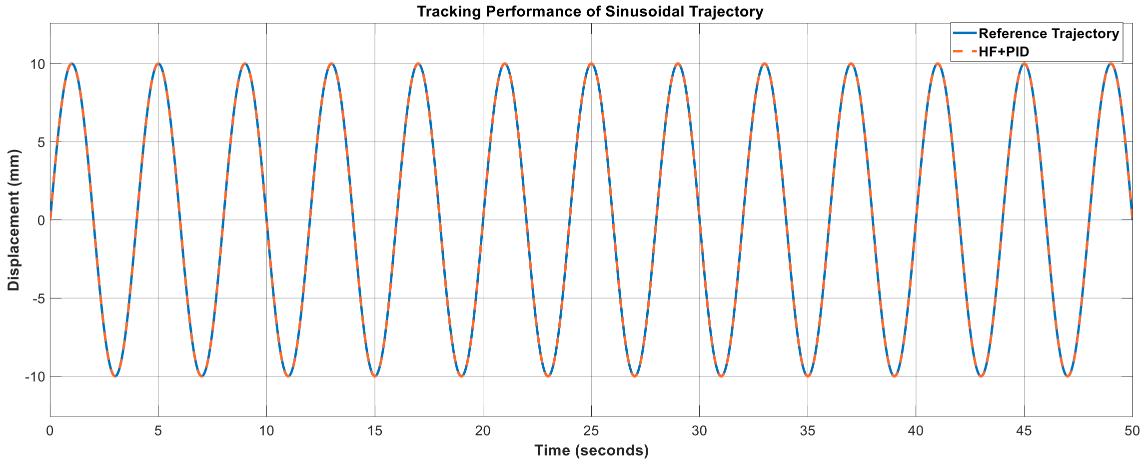

Fig. 15. Sinusoidal trajectory tracking response for hybrid fuzzy + PID controller

Table 4. Overall tracking performance of sinusoidal trajectory

Trajectory	Control Strategy	MSE	RMSE
Sinusoidal	ZN-PID	0.4546	0.6955
	Fuzzy	0.2736	0.5231
	HFPID	0.2735	0.5230
	HF+PID	0.0176	0.1326

3.2. Multi-sinusoidal Trajectory Tracking Responses

Next, multi-sinusoidal trajectory is used in perform the trajectory tracking. The following Fig. 16, Fig. 17, Fig. 18, Fig. 19 depicts the trajectory tracking responses for each controller under study. The ZN-PID controller exhibited the lowest tracking accuracy among the four controllers, showing multiple overshoots in its output response. In contrast, the HF+PID controller demonstrated the highest tracking accuracy, closely following the multi-sinusoidal trajectory with minimal errors. Additionally, the trajectory tracking responses of the FLC controller and HFPID controller were quite similar, indicating a comparable level of accuracy in tracking the multi-sinusoidal reference trajectory. Table 5 further presents the overall tracking performance of the multi-sinusoidal trajectory. The analysis is conducted to calculate MSE and RMSE values, enabling a comparison of all controllers.

Table 5 indicates that the ZN-PID controller yields high MSE and RMSE values of 3.1840 and 1.7844, respectively. This reflects a significant error in the controller's trajectory tracking performance. In contrast, both the FLC and HFPID produce nearly identical results, while the HF+PID achieves the lowest MSE and RMSE values. This demonstrates that the HF+PID controller delivers superior performance for trajectory tracking.

Table 5. Overall tracking performance for multi-sinusoidal trajectory

Trajectory	Control Strategy	MSE	RMSE
Multi-Sinusoidal	ZN-PID	3.1840	1.7844
	Fuzzy	1.8962	1.3770
	HFPID	1.8964	1.3771
	HF+PID	0.3187	0.1015

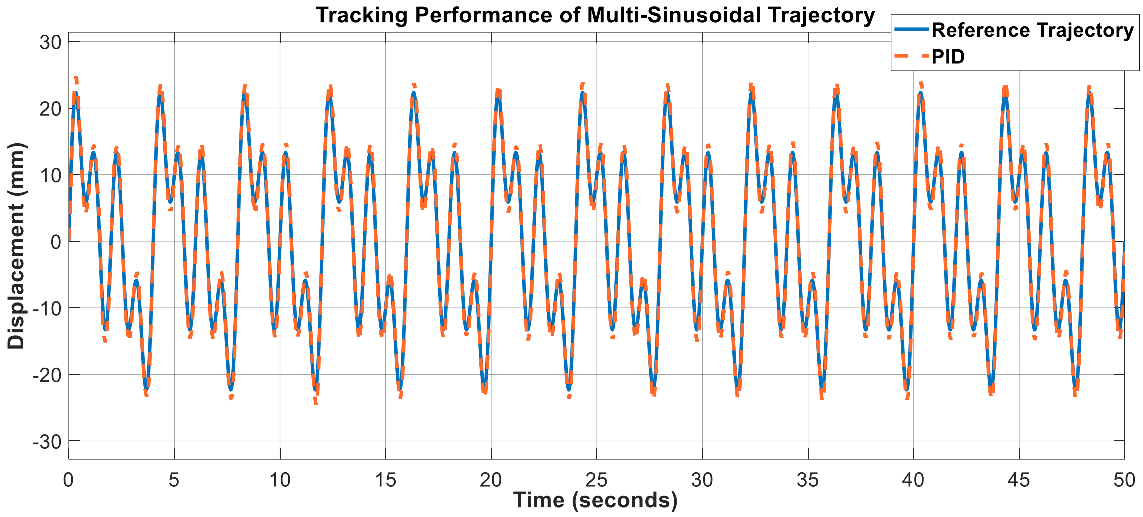

Fig. 16. Multi-sinusoidal trajectory tracking response for ZN-PID controller

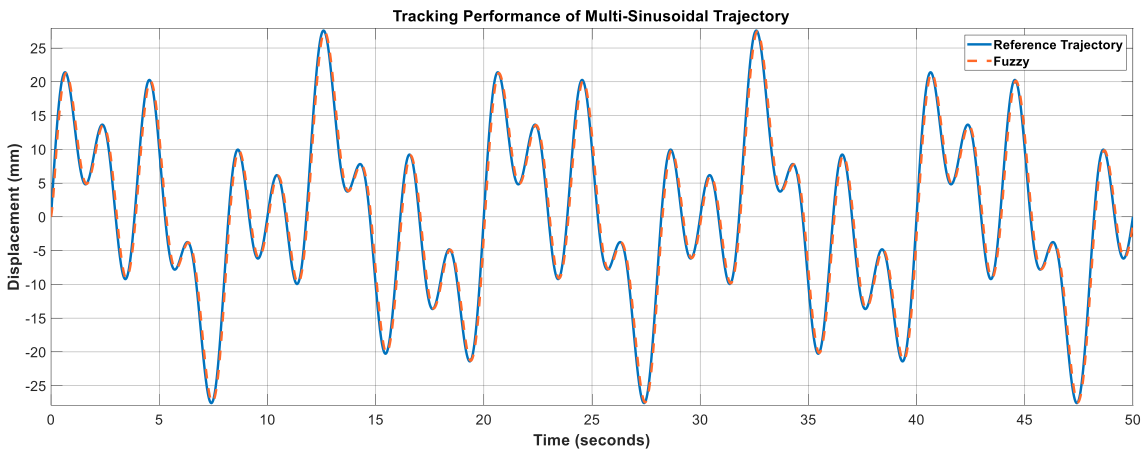

Fig. 17. Multi-sinusoidal trajectory tracking response for fuzzy logic controller

3.3. Point-to-Point Trajectory Tracking Responses

Next, point-to-point trajectory is used in perform the trajectory tracking. The following Fig. 20, Fig. 21, Fig. 22 and Fig. 23 depicts the trajectory tracking responses for each controller under study. This approach is crucial in applications requiring accurate positioning, such as automated assembly lines, CNC machines, or robotic manipulators. The ZN-PID controller exhibited the lowest tracking accuracy among the four controllers, showing multiple overshoots in its output response. In contrast, the HF+PID controller demonstrated the highest tracking accuracy, closely following the point-to-point trajectory with minimal errors. Additionally, the trajectory tracking responses of the FLC controller and HFPID controller were quite similar, indicating a comparable level of accuracy in tracking the point-to-point reference trajectory. Table 6 further presents the overall tracking performance of the point-to-point trajectory. The analysis is conducted to calculate MSE and RMSE values, enabling a comparison of all controllers.

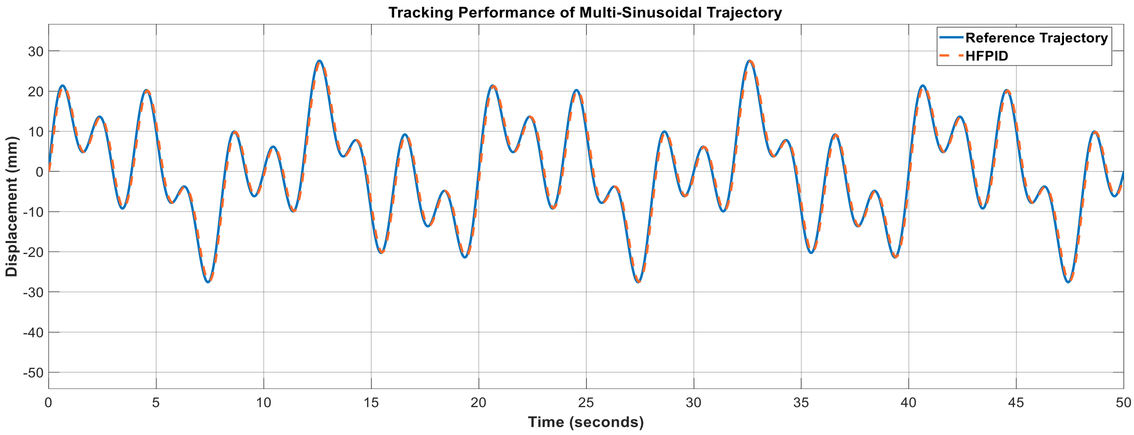

Fig. 18. Multi-sinusoidal trajectory tracking response for hybrid fuzzy PID controller

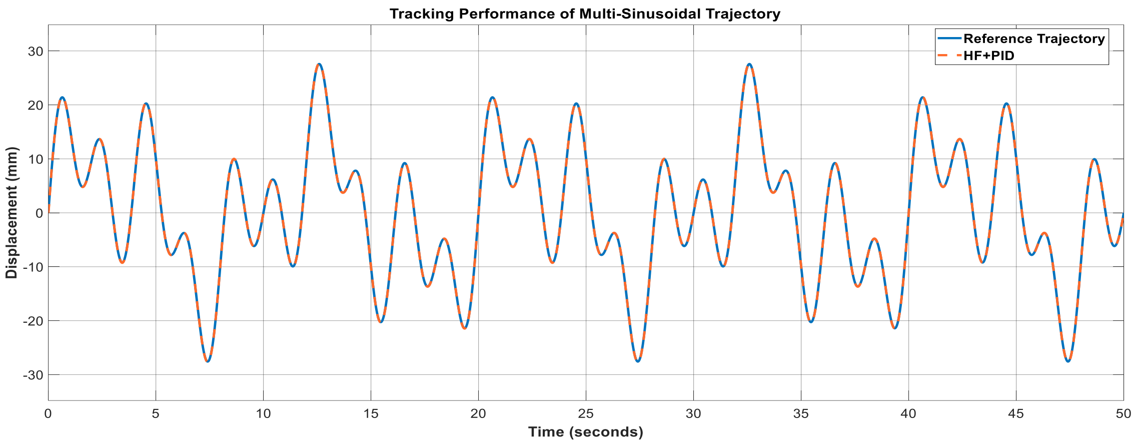

Fig. 19. Multi-sinusoidal trajectory tracking response for hybrid fuzzy + PID controller

The graph in Fig. 20 reveals significant oscillations and chattering at certain points, indicating a substantial deviation from the desired trajectory. These patterns underscore the limitations of the ZN-PID controller in achieving precise trajectory tracking. The erratic behavior and inconsistent response of the ZN-PID controller suggest difficulties in accurately following the point-to-point trajectory, leading to a higher tracking error. Conversely, the HF+PID controller demonstrates superior performance in Fig. 23. The graph displays a very small tracking error, indicating that the HF+PID controller accurately follows the reference point-to-point signal. The response of the HF+PID controller closely aligns with the desired trajectory, showcasing its exceptional accuracy and precision in trajectory tracking. The minimal deviations from the reference signal illustrate the effectiveness of the HF+PID controller in achieving highly accurate and reliable trajectory tracking.

Table 6. Overall tracking performance for point-to-point trajectory

Trajectory	Control Strategy	MSE	RMSE
Point-to-Point	ZN-PID	0.0189	0.0137
	Fuzzy	0.0022	0.0180
	HFPID	0.0022	0.0180
	HF+PID	0.0001	0.0108

In Fig. 21 and Fig. 22, the tracking performance of the FLC and HFPID controllers seems similar. This similarity is due to the switching mechanism between the PID and FLC in the HFPID controller. As a result of this switching, both controllers exhibit a comparable level of tracking performance.

Importantly, both controllers demonstrate better tracking performance than the ZN-PID controller, as evidenced by their lower tracking errors.

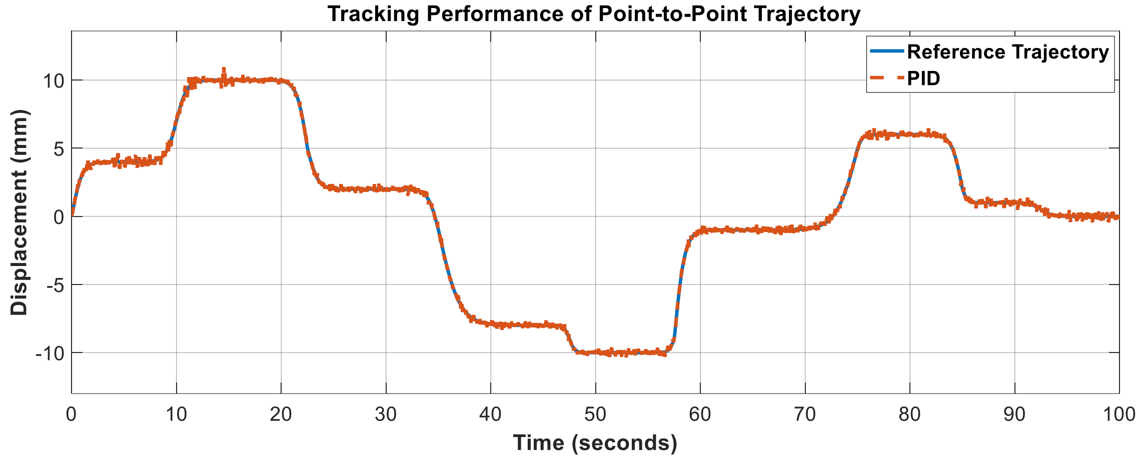

Fig. 20. Point-to-point trajectory tracking response for ZN-PID controller

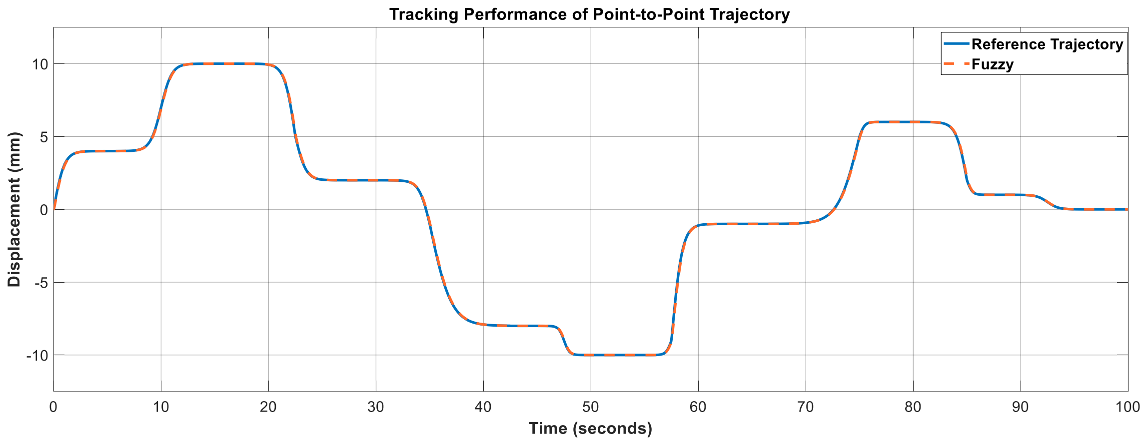

Fig. 21. Point-to-point trajectory tracking response for fuzzy logic controller

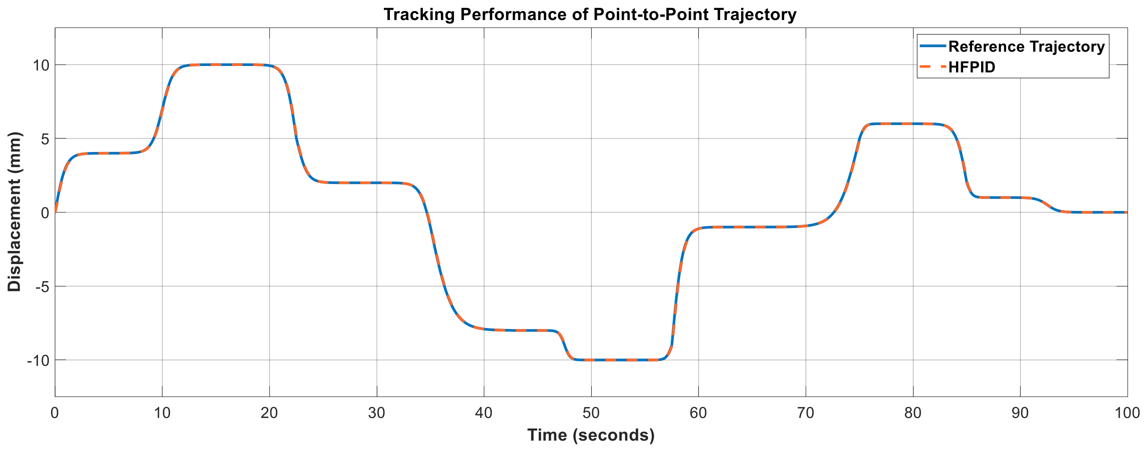

Fig. 22. Point-to-point trajectory tracking response for hybrid fuzzy PID controller

3.4. Performance Analysis

A robustness test was conducted on the point-to-point trajectory to evaluate the performance of all four controllers under varying operating conditions in the EHA system as shown in Table 7. Specifically, the mass parameter was increased to 150% of its nominal value. The objective of this test was to assess the robustness of the controllers and their ability to maintain accurate trajectory tracking despite parameter variations. Analysis of the results revealed a significant increase in the MSE value for the ZN-PID controller following the robustness test. The robustness index, which measures the deviation in performance, indicated a high value for the ZN-PID controller. This outcome suggests that the PID controller lacks robustness when operating conditions vary, as it struggled to accurately track the point-to-point trajectory with the increased mass parameter.

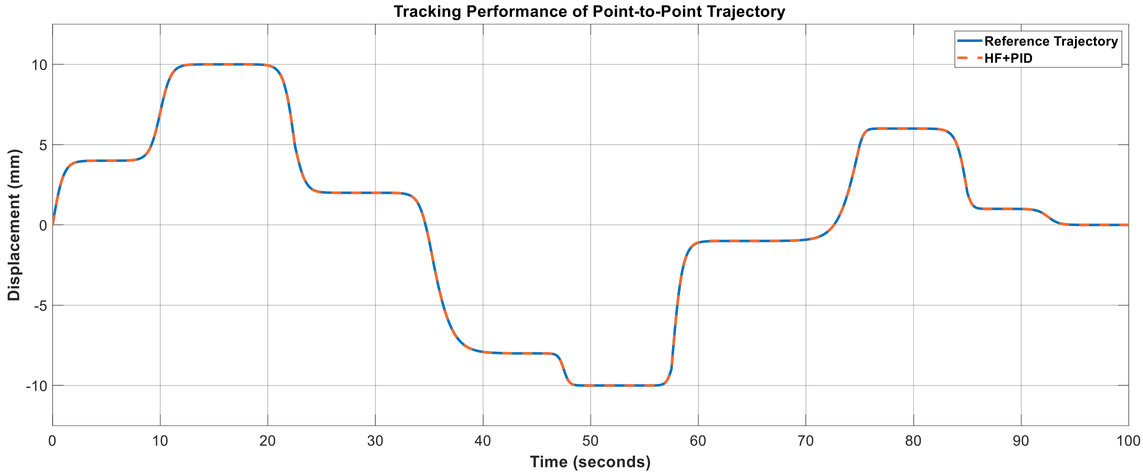

Fig. 23. Point-to-point trajectory tracking response for hybrid fuzzy + PID controller

In contrast, the FLC, HFPID, and HF+PID controllers demonstrated different behavior during the robustness test. These controllers showed a low robustness index, indicating minimal changes in the MSE value when subjected to the robustness test. This suggests that these controllers are robust to changes in operating conditions, as they maintained accurate trajectory tracking despite the increased mass parameter. The stark contrast in robustness performance between the ZN-PID controller and the other three controllers underscores the importance of advanced control strategies, such as FL and hybrid approaches, in achieving robust trajectory tracking. The ZN-PID controller's sensitivity to variations in operating conditions is likely due to its reliance on fixed parameters and limited adaptability to changes in system dynamics. In contrast, the FLC, HFPID, and HF+PID controllers, which incorporate more sophisticated control strategies, exhibit greater robustness to parameter variations.

Table 7. Tracking performance for trajectories

Trajectory	Control Strategy	MSE	RMSE	Robustness index
Sinusoidal	ZN-PID	0.4546	0.6955	-
	Fuzzy	0.2736	0.5231	-
	HFPID	0.2735	0.5230	-
	HF+PID	0.0176	0.1326	-
Multi-Sinusoidal	ZN-PID	3.1840	17844	-
	Fuzzy	1.8962	1.3770	-
	HFPID	1.8964	1.3771	-
	HF+PID	0.3187	0.1015	-
Point-to-Point	ZN-PID	0.0189	0.0137	13.7900
	Fuzzy	0.0022	0.0180	0.0454
	HFPID	0.0022	0.0466	0.0454
	HF+PID	0.0001	0.0108	0.0557

4. Conclusion

In conclusion, this paper demonstrates that the nonlinear EHA system can be effectively controlled using ZN-PID, FLC, Hybrid Fuzzy-PID (HFPID), and Hybrid Fuzzy+PID (HF+PID) controllers. The performance of the controllers is evaluated through trajectory tracking tasks, revealing that a conventional PID and fuzzy controller can improve their performance through a combined approach. This controller development addresses the challenges posed by high nonlinearity, uncertainties, and varying parameters. The simulated results show that the HF+PID controller outperforms the ZN-PID, FLC, and HFPID controllers in all tested performance characteristics during the controller assessment process. MSE and RMSE values for HF+PID controller of every trajectory tracking shows the smallest compared to other controllers which is the MSE and RMSE value for sinusoidal trajectory is 0.0176 and 0.1326, multi-sinusoidal trajectory is 0.3187 and 0.1015, and point-to-point trajectory is 0.0001 and 0.0108. The robustness and high accuracy of HF+PID controllers is crucial because they offer significant advantages in various applications, such as aviation, robotics, and cranes. Future work should focus on implementing the designed controller on hardware for real-time performance and experimenting with various types of FLC or Hybrid controllers, such as self-tuning fuzzy-PID, to further explore their potential.

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