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Enhancing Field-Controlled DC Motors with Artificial Intelligence-Infused Fuzzy Logic Controller

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Abstract

Servomotors play a pivotal role in a wide array of everyday and industrial applications. Field-controlled DC motors particularly stand out for positioning tasks owing to their advantageous speed-torque characteristics. An optical encoder, integrated with the rotor, provides feedback to a PID controller, which in turn generates corrective signals for precise motor positioning. To enhance response speed and minimize hunting, the PID controller incorporates fuzzy logic programming. This paper introduces a novel optimization design approach utilizing a Performance-Oriented Rule-Based Controller (PDFCS) in conjunction with various PID fuzzy controller design methods to attain specific performance goals. Given the criticality of constructing membership functions in fuzzy controllers, a self-optimized membership functions algorithm is proposed. Accuracy analysis demonstrates that the proposed design method achieves a 2.9-second reduction in rise time, a 2.0-second decrease in settling time, and a 1.9% reduction in overshoot compared to conventional design methods. Furthermore, robustness analysis reveals a 4.0-second improvement in rise time, a 1.7-second enhancement in settling time, and a 0.79% decrease in overshoot. These findings underscore the superior accuracy and robustness of employing the proposed performance model alongside various PID fuzzy controller design methods, compared to relying solely on conventional design approaches.

Keywords: PID Controller, DC Motors, Field-Controlled Motor, Fuzzy Controller, Intelligent Systems

1. Introduction

Servomotors are indispensable in applications requiring precise speed and position control. They are commonly used in everyday devices such as cameras, toys, and CD/DVD players, as well as in industrial systems like machine tools, robotics, radar tracking, solar photovoltaic systems, and conveyor systems. Servomotors come in two main categories: AC and DC. Both types offer unique advantages, making them suitable for different applications.

DC servomotors are often favored for their simplicity, cost-effectiveness, and efficiency. They are particularly well-suited for applications requiring lower power and simpler control mechanisms. These motors rely on a commutator and brushes to deliver current to the rotor, making them easier to control using conventional techniques. However, their mechanical design introduces wear and electromagnetic interference, which can impact long-term performance.

AC servomotors, on the other hand, benefit from advancements in power electronics and microprocessors, enabling highly accurate and dynamic control. These motors are often used in high-performance applications where precision and robustness are critical, albeit at a higher cost and with greater complexity in the control systems.

Field-controlled DC motors (FCDCM) stand out for positioning tasks due to their advantageous speed-torque characteristics. The speed of a FCDCM is regulated by adjusting the magnetic field produced by the stator, allowing precise control over the motor's operation. This approach maintains consistent speed across a wide range of torque demands, making FCDCM particularly well-suited for applications requiring stable and precise positioning. Unlike armature-controlled motors, where speed control is achieved by varying the armature current, field control minimizes speed variation with changing torque, resulting in improved stability and reliability [1], [2], [3]. In recent years, artificial intelligence (AI) has found extensive applications across various domains, including pattern recognition [4],

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[5], computer networking [6], information security [7], wireless communications [8], [9], [10], and beyond. Among these AI technologies, Fuzzy Logic systems have demonstrated significant practical implementations, particularly in control systems, showcasing their ability to manage uncertainty and imprecision effectively. With fuzzy logic, the system response is smoother and the PID controller response is adjusted based on the magnitude of the error signal [11], [12], [13]. It will be called a PID Fuzzy Controller, or simply PID FC. Some recent applications of PID FC can be found in [14], [15], [16] and others

Our prior investigations [17], [18], [19] extensively explored and classified diverse design options for the PID FC. In this study, we enhance these design methodologies by prioritizing key performance metrics of the controlled process, particularly focusing on rise-time (Tr) and percentage overshoot (PO). To accomplish this, we advocate for the adoption of a Performance-Oriented Rule-Based Controller (PDFCS), seamlessly integrable with any controller design method. Consequently, this approach bridges the gap between a pragmatic PID FC and an idealized one. Additionally, we introduce a simple approach for determining membership functions for a PID FC, enabling even novices to systematically develop a set of membership functions for specific linguistic variables.

Furthermore, papers [20], [21], and [22] proposed an improved version of the PID FC by clustering FC behaviors. They removed the need for predefined parameters for clustering using self-clustering algorithms. The resulting PID FC was shown to be very efficient and fast.

The structure of this paper unfolds as follows: Section 2 delves into relevant aspects concerning FCDCM. Section 3 presents our novel method, leveraging a PDFCS to achieve the desired performance for the PID FC. Section 4 conducts a comparative analysis of performance between the proposed design method and existing methodologies. Finally, Section 5 offers conclusions drawn from our proposed approach.

2. Field-Controlled DC Motors (FCDCM)

The PID controller, widely used in closed-loop control systems, generates a control signal u(t) based on three components: proportional, integral, and derivative. The formula for a PID controller is expressed as:

$$u(t) = Kp\, e(t) + Ki \int e(t)\, dt + Kd\, de/dt \quad (1)$$

Note: e(t): The error, defined as the difference between the desired output (r) and the actual output (y): e(t) = r – y; Kp: The proportional gain, which determines the magnitude of the control action proportional to the current error. Higher Kp values lead to faster responses but can increase overshoot; Ki: The integral gain, which addresses accumulated error over time by integrating e(t). This term ensures that the system reaches and maintains the desired setpoint, eliminating steady-state errors; Kd: The derivative gain, which anticipates future error by considering the rate of change of e(t). It improves system stability by damping oscillations and overshoot.

The PID controller works by combining these components to achieve a balance between speed of response, accuracy, and stability:

Kpe(t): Provides immediate corrective action in response to the error signal, aiming to reduce it directly.

Ki ∫e(t)dt: Eliminates residual errors that may persist after the proportional response has stabilized the system.

Kd de(t)/dt: Prevents excessive changes in the signal, helping the system avoid overshoot and oscillations.

By tuning the values of Kp, Ki, and Kd, the controller can be adapted to different system dynamics and performance requirements. A higher Kp may speed up response time, but excessive values could result in instability. Similarly, Ki helps correct long-term errors but may introduce lag, and Kd enhances stability but could amplify noise in the error. Servomotor systems are made up of the speed-controlled motor, a position sensor and a feedback and control system. Each of these elements is discussed below.

2.1. Speed Control of a Brushed DC Motor

The most common method of speed control for a brushed DC motor is through regulation of flux produced by the field winding. The speed of the DC motor is inversely proportional to the flux produced by the field winding [23].

The major advantage of field control is that the motor speed remains substantially constant over a wide range of torques. The alternative method of speed control of a brushed DC motor is through control of the armature current. Motor speed is directly proportional to the armature current [24]. The motor speed falls off with torque. For this reason, field control is preferred to armature control for positioning applications.

2.2. Rotary Encoders for Position Sensing

Rotary optical encoders are widely used to measure the position of the motor shaft. These are made up of an LED light source, a code disc, a photo sensor and a signal processor [24]. Optical encoders are of two types, incremental and absolute. Incremental encoders generate an output signal each time the motor shaft rotates a certain amount. The control system therefore has to provide the reference point to achieve the desired final positioning. Absolute encoders provide a unique output for each disc position but are more expensive. Multi-turn optical encoders have a geared mechanism that enables position tracking over multiple turns of the motor shaft. Encoders using other forms of sensing are also available.

2.3. Position Control of DC Motor with Fuzzy PID Controller

From the above literature survey, a field-controlled DC motor is better suited for a position control application than an armature controlled motor due to its speed remaining substantially constant with the change in torque. The DC motor must be fitted with an optical encoder to sense position. The encoder selected can be an incremental encoder or an absolute encoder depending upon the application. Its signals are fed to a processor which generates the error signal that is fed through an amplifier to a switch-mode motor driver to vary the field current of the DC motor to drive the motor to the desired position. The PID can be provided with fuzzy logic to improve the speed of response and to prevent hunting before the final position is achieved. Based on the feedback signal, the DC motor is rapidly accelerated and then as the motor reaches close to its set final position, the speed is decreased in steps until the rotor stops at the set the final position.

3. Methodology

To achieve optimal performance output, this paper proposes two key modules: a PDFCS aimed at attaining the desired performance of any selected system, and an optimal membership functions algorithm designed to obtain the most effective membership functions for representing fuzzy variables.

3.1. Comparison of PID FC Types

The paper provides a comprehensive evaluation of various types of PID FCs, including Incremental PID FC, Velocity Algorithm PID FC, and others, emphasizing their distinct characteristics and application contexts. Traditional PID FC serves as the standard form, where proportional, integral, and derivative gains (Kp, Ki, and Kd) are either fixed or adjusted based on fuzzy rules, making it suitable for general-purpose control applications with stable and predictable system dynamics. Incremental PID FC takes a different approach by adjusting the control output incrementally, based on changes in the error and its derivatives, ensuring smooth transitions. This type is particularly effective in scenarios like servo mechanisms and process controls that require gradual changes.

The Velocity Algorithm PID FC, in contrast, focuses on the rate of change of the control signal rather than its absolute value, which reduces overshoot and enables faster settling times. It is ideal for high-speed systems, such as robotic arms or conveyor belts, where rapid response is crucial. Proportional-Derivative Control with Integral Action (PDCIA) combines the fast response characteristics of proportional-derivative control with an integral term to eliminate steady-state errors. This makes it well-suited for systems requiring both speed and long-term accuracy, such as temperature or pressure control applications. Similarly, Hybrid Proportional-Derivative Control with Proportional-Integral Action (HPDCPIA) introduces a hybrid structure to achieve a balance between fast response and minimal overshoot, enhancing stability in complex systems like motor drives and power converters.

The Decomposed PID Control Strategy (DPCS) takes a unique approach by separating proportional, integral, and derivative components for independent tuning, offering significant flexibility at the cost of added complexity. This method is most appropriate for highly specialized systems, such as aerospace and advanced robotics, where precise tuning of each component is essential. Lastly, the Variable Structure PID FC (VSPID FC) adapts dynamically to changing system states using variable structures in its rule base. This capability makes it particularly effective for nonlinear systems or applications subject to frequent disturbances, such as in the automotive sector. The diverse focus of these PID FC types—whether on incremental adjustments, velocity, or specific combinations of control components—demonstrates their adaptability in meeting a wide range of control requirements, showcasing the versatility and utility of PID Fuzzy Controllers across varied domains.

3.2. Performance-Oriented Rule-Based Controller (PDFCS)

Prior research [17], [18] has compared the performance of various methods for designing the PID FC; however, these approaches often overlook the essential performance criteria required for the optimal operation of the controlled plant. In practical applications, it is imperative for every plant to satisfy specific performance measures to ensure proper functionality. The structure and content of the rules embedded within a PID FC rule-base have been extensively examined in [17]. Figure 1 illustrates the time response of FCDCM, shedding light on their characteristic behavior.

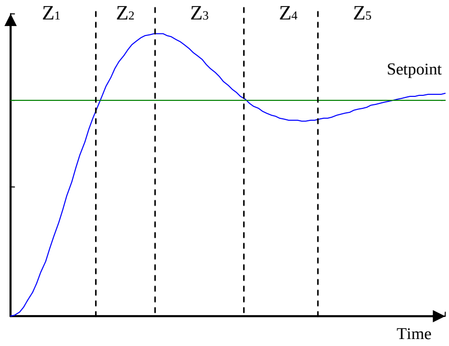


Figure 1. The Response of the Field-Controlled DC Motors

To expedite the rise-time (Tr), it's advisable to ensure a positive control action U(k) within zone 1, regardless of the measured input values: error e(k), error change de(k), and error sum se(k). Conversely, to mitigate percentage overshoot (PO), a negative control action U(k) within zone 2 is recommended. Determining the optimal Tr and PO is crucial for the plant's effective operation. Hence, the following rules are proposed:

R1: IF the Tr is characterized by FS1, THEN the U(k) is positive.

R2: IF the PO is characterized by FS2, THEN the U(k) is negative.

Here, FS1 denotes a fuzzy set defined on the fuzzy variable Tr, while FS2 represents a fuzzy set defined on the fuzzy variable PO. Figure 2 illustrates the definition of these fuzzy sets: Threshold 1 signifies the Tr threshold that the plant should not exceed, while threshold 2 indicates the desired PO that the plant should aim for.

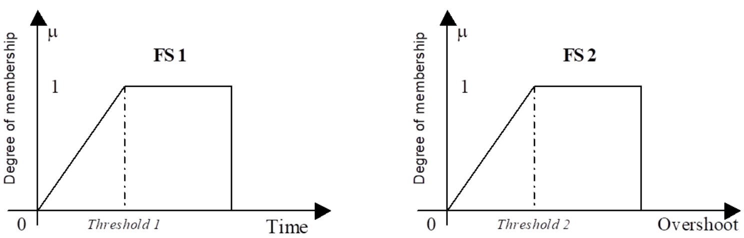


Figure 2. Fuzzy Sets for Tr and PO

Before reaching threshold 1 (the desired Tr), the PID FC output undergoes an ascent to approach the target setpoint. This ascent inevitably leads to an PO as the system output accelerates. To address this PO, metarule 2 comes into play to regulate it. If the PO exceeds threshold 2 (the expected PO), the PID FC output needs to decrease to offset the previous increase. Importantly, these two metarules are adaptable to any method of designing a PID FC.

To enhance the efficiency of rule-base design, we propose a bifurcation of the rule-base of the PID FC into two distinct modules. One module leverages multiple input variables (e(k), de(k), and se(k)) to generate a nominal output. Conversely, the other module operates exclusively on a subset of input variables (Tr and PO) to evaluate performance and fine-tune the nominal output; this module is referred to as the PDFCS.

This approach is underpinned by the notion that performance conditions correspond to a limited number of regions in the input space, thus necessitating only a handful of rules to capture them effectively. Consequently, it obviates the need to consider all potential combinations of input variables when formulating rules for performance management.

The controller's output is determined as the average of the outputs generated by the nominal control module and the performance-handling module, following the algorithm depicted in figure 3. Within the provided pseudo-code, the function Calculate_U2_using_PDFCS acts as a placeholder to compute the control action U2[k] using the proposed PDFCS Fuzzy Inference System. The parameters such as time, desired_rise_time, percent_overshoot, and desired_percent_overshoot correspond to the respective system attributes, including the current time, the desired rise time (Tr), the actual percent overshoot, and the desired percent overshoot. These parameters play a crucial role in aligning the controller's performance with the system's dynamic requirements.

```
% To calculate the control action U[k] using the Fuzzy Inference System (FIS) based on the selected input,
% we follow the outlined procedure:
% Input is selected depending on the kind of controller.
if time < desired Tr
   % Calculate by FIS U2[k] using proposed PDFCS
   U2[k] = Calculate_U2_using_PDFCS(time, desired_rise_time);
   % Combine the control action U[k] with U2[k] and take the average
   U[k] = U[k] + U2[k] / 2;
end
if PO > desired PO
   % Calculate by FIS U2[k] using proposed PDFCS
   U2[k] = Calculate_U2_using_PDFCS(percent_overshoot, desired_percent_overshoot);
   % Combine the control action U[k] with U2[k] and take the average
   U[k] = U[k] + U2[k] / 2;
end
```

Figure 3. Pseudocode for calculating the control action U[k] using the PDFCS

3.3. Refinement of Membership Functions

In fuzzy controllers, the accuracy of control heavily relies on the design of membership functions, which represent fuzzy linguistic variables. While traditional designs often use equally spaced, isosceles triangular membership functions for simplicity, such configurations may fail to achieve optimal performance in nonlinear systems.

Figure 4 illustrates the membership functions for the fuzzy variable x, encompassing linguistic terms such as "Negative," "Zero," and "Positive." These membership functions are constructed using triangular shapes, defined across the universe of discourse [−Ux, Ux]. The peaks of the triangles represent the points of maximum membership for each fuzzy set, while the bases determine the range of influence.

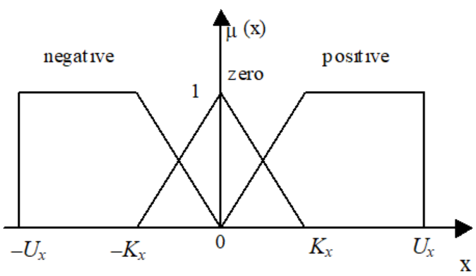


Figure 4. Membership Functions for Fuzzy Variable x

To ensure a smooth transition between fuzzy sets, the bases overlap, creating regions where input values belong partially to multiple sets. This overlapping is critical for achieving robust and gradual control actions, as it allows the system to account for uncertainties and avoid abrupt changes in control outputs. For example, an input value near the transition from "Negative" to "Zero" would activate both sets to varying degrees, leading to a blended response that reflects the system's state more accurately.

The placement of the Kx points, which define the peaks and boundaries of the membership functions, is guided by performance requirements. By adjusting these parameters, the fuzzy controller can be tailored to prioritize specific system objectives, such as minimizing rise time or reducing overshoot. Additionally, the self-optimization mechanism described earlier [17], [19] enables iterative refinement of these parameters to adapt to dynamic or nonlinear system behaviors.

The proposed algorithm incorporates a self-optimization mechanism to dynamically determine and adapt membership functions, aligning them with specified performance objectives. Initially, a set of triangular membership functions is defined across the universe of discourse for each fuzzy variable, such as error, error rate, and accumulated error. These membership functions are systematically refined through an iterative process. In each iteration, key performance metrics, including Tr, Ts, and PO, are evaluated to assess the controller's response to input variations. Based on these evaluations, the algorithm applies a gradient-based optimization method to adjust the parameters of the membership functions, such as their base and peak positions. The optimization objective focuses on minimizing an aggregate error function that reflects deviations from the desired thresholds for Tr, Ts, and PO. The process continues until convergence criteria are met, where changes in performance metrics between iterations fall below a predefined threshold. This ensures that the optimization process achieves both stability and computational efficiency.

3.4. Workflow of the PID FC with Fuzzy Logic Integration

The integration of fuzzy logic into the PID controller introduces adaptive capabilities, allowing the controller to dynamically adjust its parameters based on the system's error characteristics. This process begins with input acquisition, where the system error (e(k)) and its rate of change (de(k)) are collected at each sampling interval. These crisp inputs are then fuzzified by converting them into fuzzy values using predefined membership functions, with linguistic variables such as "Negative," "Zero," and "Positive" representing the fuzzy states of the inputs. Next, a set of fuzzy logic rules is evaluated to determine the necessary adjustments for Kp, Ki, and Kd, followed by an inference mechanism that combines the activated rules to calculate fuzzy output adjustments for these parameters. The max-min composition method is used to aggregate the outputs of the rules.

The resulting fuzzy values for Kp, Ki, and Kd are then defuzzified back into crisp values using a defuzzification method, such as the Center of Area approach. With these dynamically updated gains, the PID controller generates the control signal u(t) by applying the updated parameters to compute the system's response. Finally, the computed control signal u(t) is applied to the system, ensuring its behavior aligns with the desired performance objectives. The steps of this adaptive PID Fuzzy Controller (PID FC) algorithm are detailed further in the pseudocode illustrated in figure 5.

1. Initialize membership functions and fuzzy rules.
2. At each sampling interval:
   a. Measure error *e(k)* and error rate *de(k)*.
   b. Fuzzify inputs (*e(k), de(k)*).
   c. Apply fuzzy rules to determine fuzzy adjustments for *Kp, Ki, Kd*.
   d. Aggregate and defuzzify outputs for *Kp, Ki, Kd*.
   e. Update PID gains with defuzzified values.
   f. Compute control signal *u(t)* using updated PID formula:
      $u(t) = Kp * e(t) + Ki * \int e(t)\, dt + Kd * de(t)/dt$.
   g. Apply *u(t)* to the system.
3. Repeat until system reaches desired state or steady state.

Figure 5. Pseudocode for the workflow of the PID FC

4. Results and Discussion

4.1. Simulation Setup

The simulations were conducted using MATLAB with the Fuzzy Logic Toolbox developed by MathWorks to evaluate the proposed PID FC designs. The configuration parameters of the fuzzy system adhered to those described in previous studies [17], [18], and [19]. Consistently across all simulations, the FCDCM was configured with a desired angular displacement of 50 radians and a sampling interval of 1 second.

The fuzzy linguistic control rules were defined, and the membership functions for the linguistic variables—error (e), error derivative (de), summation of errors (se), and control action (U)—were determined using the optimal membership functions method described in the previous chapter. The universes of discourse for these variables were as follows: Error (e): [-50, 50], de: [-40, 40], se: [-100, 100], and Control action (U): [-40, 40].

For implementing the proposed PDFCS, specific thresholds were established to guide the control system: Threshold_1: A desired rise time (Tr) of 5 seconds and Threshold_2: A percentage overshoot (PO) of 6%.

To enhance inference and control accuracy, specific configurations were implemented in the fuzzy control system. The MIN operator was selected as the AND connective for processing antecedents and for performing the fuzzy implication operation, while the MAX operator was utilized as the OR connective to handle relationships between rules. For defuzzification, the center of area (COA) was employed, ensuring that the fuzzy outputs were effectively converted into precise crisp values, thereby improving the overall precision and reliability of the control system.

The primary objective of the simulations is to showcase the effectiveness of the proposed PID design method when applied to second-order systems. To assess the performance of the proposed PDFCS, three critical performance metrics have been meticulously selected: transient response, error integral criteria, and robustness.

Robustness, a crucial attribute of any controller, refers to its ability to maintain stable performance in the face of significant parameter variations. Traditionally, robustness is evaluated by analyzing the controller's behavior under parameter values that deviate from the nominal design. While inherently empirical, assessing the effects of parameter variations on PID FC design methods provides a quantitative measure of robustness.

A recommended approach to quantify robustness involves varying the defuzzification method parameter. While the COA defuzzification method is typically employed during FC design, evaluating the controller's performance using the bisector of area (BOA) defuzzification method offers insights into its robustness [11].

4.2. Performance Evaluation

The performance of a control system is commonly assessed using error integral criteria, which provide quantitative measures of the system's response over time. Metrics such as the Integral of Absolute Error (IAE) and the Integral of Time-weighted Absolute Error (ITAE) are particularly important in evaluating the effectiveness of controllers. The IAE measures the total absolute error over time, focusing on minimizing the magnitude of deviations from the desired setpoint. A lower IAE reflects improved overall accuracy and better adherence to the setpoint.

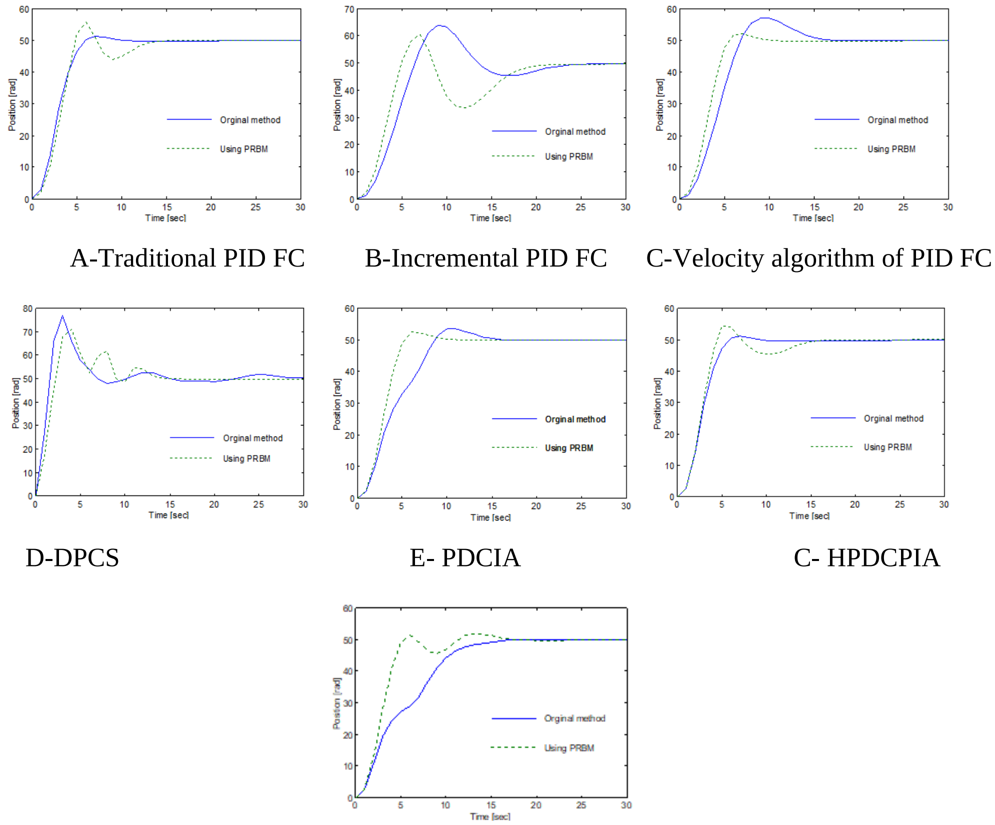
$$IAE = \int_0^\infty | e(t) | \, dt \tag{2}$$

In contrast, the ITAE assigns greater weight to errors that persist over time by multiplying the absolute error by time, thereby penalizing sustained deviations. This metric promotes quicker settling times and smoother responses, with lower ITAE values indicating a controller's robustness and efficiency in mitigating long-term errors.

$$ITAE = \int_0^\infty t \, | e(t) | \, dt \tag{3}$$

The evaluation of various methods for designing PID FCs, including the proposed PDFCS, provides critical insights into the comparative effectiveness of these approaches in meeting control objectives, highlighting their strengths in achieving accuracy, stability, and responsiveness.

The comparisons between the step responses of the FCDCM system using different design methods reveal notable differences in terms of Tr, settling-time, and PO. Upon examining the results presented in figure 6, table 1 and table 2, it becomes evident that the incorporation of the PDFCS consistently leads to improvements in key performance metrics across all design methods. Specifically, employing the PDFCS alongside traditional PID FCs, incremental PID FCs, velocity algorithm FCs, Proportional-Derivative Control with Integral Action (PDCIA), HPDCPIA, and VSPID FCs results in reductions in Tr, settling-time, and PO.



A-Traditional PID FC B-Incremental PID FC C-Velocity algorithm of PID FC

D-DPCS E- PDCIA C- HPDCPIA

G- VSPID FC

Figure 6. Step response of field-controlled DC motor system

One notable exception is observed in the case of the Decomposed PID Control Strategy (DPCS), where the independent tuning requirements of its proportional, integral, and derivative components introduce complexities that hinder the performance improvements achieved by the PDFCS. This underscores the importance of considering the interaction between control components and the overall system dynamics when designing PID controllers.

Furthermore, the comparison between the average performance metrics of the original design methods and the PDFCS-enhanced methods highlights the significant performance enhancements achieved by the proposed approach. The reduction in Tr by 2.9 seconds, decrease in settling-time by 2.0 seconds, and concurrent reduction in PO by 1.9% demonstrate the effectiveness of incorporating the PDFCS in improving control system performance (see table 1 and table 2). It's worth noting the impracticality of manually determining control rules, particularly when dealing with systems exhibiting significant PO and deviation from the reference response, as observed in the case of the incremental PID FC method. This emphasizes the need for automated and adaptive control methodologies, such as the PDFCS, to effectively handle complex system dynamics and achieve precise control objectives.

Table 1. Performance of PID FC

PID FC Type	Tr (Sec)	Ts (Sec)	PO (%)	IAE	ITAE
Traditional PID FC	6	9	2.680	175.309	863.896
Incremental PID FC	7	23	27.924	314.280	2585.9
Velocity algorithm FC	7	14	13.993	261.639	1644.9
DPCS	2	15	55.744	165.804	1055.4
PDCIA	8	14	7.028	246.595	1490.1

HPDCPIA	6	9	2.231	174.261	889.785
VSPID FC	16	16	0.060	293.486	1957.9
Average	7.43	14.29	15.67	233.05	1498.27

Table 2. Performance of PID FC merged with PDFCS

PID FC Type	Tr (Sec)	Ts (Sec)	PO (%)	IAE	ITAE
Traditional PID FC	4	12	11.788	206.023	1157.6
Incremental PID FC	5	20	21.045	308.776	2856.2
Velocity algorithm FC	6	8	4.145	188.893	969.38
DPCS	3	13	41.963	176.111	1007.3
PDCIA	5	8	4.953	178.297	856.61
HPDCPIA	4	14	8.548	189.284	1098.7
VSPID FC	5	16	3.983	189.807	1076.9
Average	4.57	12.29	13.78	205.31	1288.96

In conclusion, the performance evaluation results underscore the efficacy of the proposed PDFCS in enhancing the performance of PID FCs for FCDCM systems. By addressing key performance criteria and providing systematic design methodologies, the PDFCS offers a solution for achieving precise and efficient control in various applications.

4.3. Robustness Test

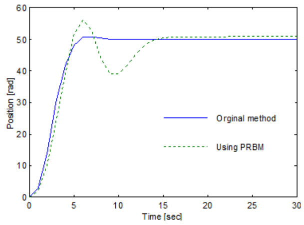
The robustness test assesses the system's resilience to parameter variations, particularly focusing on changes in the defuzzification methods used within the PID FC. During this evaluation, the Center of Area (COA) defuzzification method, originally employed during the design phase, was replaced with the Bisector of Area (BOA) to analyze the controller's adaptability. COA determines control actions by averaging the output to the centroid of the aggregated membership functions, ensuring balanced and stable control actions. In contrast, BOA divides the aggregated fuzzy set into two regions of equal area, emphasizing a symmetrical distribution of control signals. These variations introduce subtle changes in how control actions are derived, challenging the controller's ability to maintain performance under differing operational constraints.

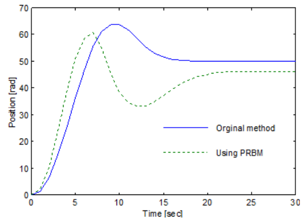
The results, illustrated in figure 7 and detailed in table 3 and table 4, reveal the impact of integrating the proposed PDFCS across various design methods on the robustness of the control system. These findings underscore the adaptability and effectiveness of the PDFCS in maintaining consistent performance, even when subjected to variations in defuzzification approaches.

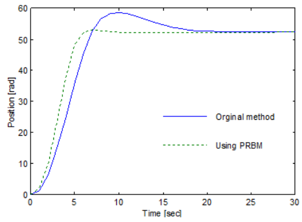
Overall, the results indicate that integrating the PDFCS consistently leads to improvements in key performance metrics, including Tr, settling-time, and PO, across all design methods. Notably, the exception observed in the case of the DPCS method can be attributed to the inherent complexities associated with its independent tuning requirements, which hinder the robustness enhancements achieved by the PDFCS.

By considering the average values of the results presented in table 3 and table 4, it becomes evident that utilizing the PDFCS with all design methods yields substantial improvements in robustness compared to relying solely on the original design methods. The reduction in Tr by 4.0 seconds, decrease in settling-time by 1.7 seconds, and concurrent reduction in PO by 0.79% underscore the effectiveness of incorporating the PDFCS in enhancing the robustness of PID FCs for FCDCM systems.

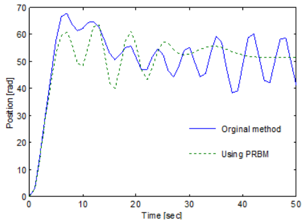
Figure 7 visually illustrates the robustness test results using the BOA defuzzification method, showcasing the performance of each design method both individually and merged with the PDFCS. The consistent trend of improved performance with the PDFCS integration emphasizes its role in enhancing the robustness of the control system across various operating conditions and parameter variations.

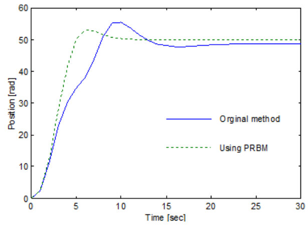


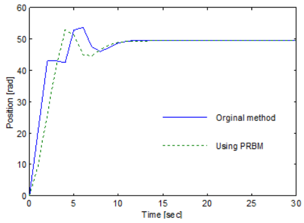




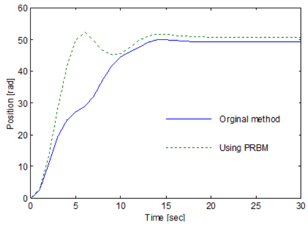
A-Traditional PID FC B-Incremental PID FC C-Velocity algorithm of PID FC







D-DPCS E- PDCIA C- HPDCPIA



G- VSPID FC

Figure 7. Robustness test using BOA defuzzification method

In conclusion, the robustness analysis reaffirms the efficacy of the proposed PDFCS in improving the resilience of PID FCs for FCDCM systems. By providing a systematic and adaptive control methodology, the PDFCS offers a practical solution for mitigating the effects of uncertainties and disturbances, thereby ensuring reliable and stable performance in real-world applications.

Table 3. Robustness test for PID FC

PID FC Type	Tr (Sec)	Ts (Sec)	PO (%)	IAE	ITAE
Traditional PID FC	6	8	1.514	172.881	924.759
Incremental PID FC	7	23	27.726	297.203	2177.3
Velocity algorithm FC	7	18	17.224	337.902	3631.3
DPCS	11	50	12.837	456.641	5728.6
PDCIA	9	13	2.269	175.672	928.253
HPDCPIA	5	14	3.538	170.201	912.560
VSPID FC	16	16	None	311.801	2422.1
Average	8.71	20.29	9.30	274.61	2389.27

Table 4. Robustness test for PID FC merged with PDFCS

PID FC Type	Tr (Sec)	Ts (Sec)	PO (%)	IAE	ITAE
Traditional PID FC	5	9	2.955	245.951	1976.1
Incremental PID FC	5	25	21.524	391.646	5179.0
Velocity algorithm FC	5	18	6.059	249.823	2540.8
DPCS	5	46	17.738	391.780	6859.2

PDCIA	4	6	3.982	134.079	712.61
HPDCPIA	4	8	2.819	223.618	1777.0
VSPID FC	5	18	4.486	205.570	1553.8
Average	4.71	18.57	8.51	263.21	2942.64

4.4. Key Findings

The discussion highlights the significant outcomes of the investigation into PID FC methodologies, emphasizing the performance enhancements and robustness achieved through integrating the PDFCS. In terms of performance evaluation, the proposed PDFCS consistently delivers faster rise times (Tr) and settling times (Ts) compared to conventional PID FC design methods. While the Decomposed PID Control Strategy (DPCS) requires independent tuning of its components, applying PDFCS across all design methods results in notable improvements in performance metrics. Robustness tests further demonstrate the effectiveness of PDFCS; when the defuzzification method is varied from COA to BOA, the PDFCS-enhanced designs maintain faster Tr and Ts, except in the case of the DPCS method. Overall, the integration of PDFCS enhances robustness across different design approaches, underscoring its capability to achieve desired performance criteria.

Quantitatively, the application of PDFCS across all design methods yields significant gains. Rise times are reduced by an average of 2.9 seconds, settling times decrease by 2.0 seconds, and overshoot is lowered by 1.9% compared to original design methods. Robustness analysis provides even more compelling evidence, showing a reduction in Tr by 4.0 seconds, Ts by 1.7 seconds, and overshoot by 0.79%. These findings reinforce the conclusion that integrating PDFCS with various PID FC design methods offers substantial improvements in both performance metrics and robustness, far surpassing conventional design approaches.

The proposed PDFCS holds immense potential for real-world applications requiring precise and robust motor control. In industrial automation, PDFCS can enhance the positioning accuracy and responsiveness of robotic arms, improving production efficiency and reducing errors. Similarly, in automated guided vehicles (AGVs) and drone navigation, PDFCS improves stability and precision, even under dynamic conditions such as varying loads or environmental changes. While this study primarily focuses on theoretical development and simulation-based validation, future work will prioritize deploying the controller in practical systems. This will enable empirical evaluation, offering opportunities for further refinement and real-world impact.

4.5. Potential Implementation Challenges

Implementing the PDFCS alongside existing PID FC methods may present several challenges. Firstly, integrating the PDFCS into existing control systems may require significant modifications to the control algorithm, potentially disrupting the system's stability and performance. Additionally, determining the optimal parameters and rules for the PDFCS could be challenging, as it relies on specific performance criteria that may vary across different applications.

However, these challenges can be addressed through careful system analysis and testing. Prior to implementation, thorough simulations and modeling can help assess the impact of integrating the PDFCS on system dynamics and performance. Furthermore, employing robust optimization techniques and heuristic algorithms can aid in the identification of optimal PDFCS parameters and rules tailored to the specific requirements of the control system.

By systematically addressing these implementation challenges and leveraging advanced simulation tools and optimization techniques, the proposed PDFCS can be effectively integrated into existing control systems, ensuring improved performance and robustness. Such thorough preparation and analysis provide confidence in the acceptability and effectiveness of the proposed method in real-world applications.

Parameter tuning in fuzzy logic-based controllers, particularly within the context of PDFCS, presents a notable challenge for certain applications. The design and adjustment of membership functions and fuzzy rules often require a deep understanding of both the system dynamics and control objectives. In systems with high nonlinearity or where dynamics change frequently, static parameter configurations may fail to deliver optimal performance, necessitating frequent recalibration. Additionally, achieving a balance between rise time, settling time, and overshoot while minimizing computational overhead can be a complex, iterative process. For industrial or real-time applications, the effort and computational resources needed to fine-tune parameters might render the approach less practical without advanced optimization techniques or adaptive algorithms. This highlights the need for developing automated or self-tuning mechanisms, such as machine learning or evolutionary algorithms, to simplify the tuning process and enhance the controller's applicability to a broader range of dynamic systems.

4.6. Comparative Analysis with Advanced Control Techniques

To situate the PDFCS within the broader framework of control theory, a comparative analysis was conducted using findings from existing literature on advanced control techniques, including adaptive control and Model Predictive Control (MPC). These techniques, renowned for their ability to manage dynamic systems with varying parameters, provide a robust benchmark for evaluating the performance and applicability of PDFCS. Adaptive control is known for dynamically adjusting its parameters to adapt to system variations, while MPC leverages system models to predict and optimize control actions over a future horizon. The analysis utilized data from published studies and reviews on these methods in comparable applications, such as motor control and industrial systems, focusing on key performance indicators including *Tr, Ts, PO,* robustness, computational complexity, and adaptability.

The findings highlight notable differences and advantages. In terms of performance metrics, MPC demonstrates competitive rise and settling times compared to PDFCS but often exhibits higher overshoot due to its reliance on precise model accuracy. Adaptive control, while robust and responsive, tends to lag in settling time because of adaptation delays [13], [23], [24]. PDFCS, by contrast, achieves a favorable balance with competitive rise and settling times and minimal overshoot, without the need for extensive modeling or prolonged adaptation processes. Regarding robustness, both MPC and adaptive control perform well under varying conditions, although MPC's dependence on accurate models can result in degraded performance when unmodeled dynamics are present [13], [23], [24]. PDFCS, with its rule-based adaptability, matches or exceeds this robustness while avoiding the complexities of model fidelity and parameter tuning.

In computational complexity, PDFCS outperforms both MPC and adaptive control, making it particularly suited for real-time systems with limited processing power. MPC's optimization algorithms are computationally intensive and less feasible for resource-constrained environments, whereas adaptive control requires moderate computational resources for real-time parameter tuning [13], [23], [24]. PDFCS, being computationally efficient, is ideal for applications where simplicity and resource constraints are key considerations. In terms of application suitability, MPC excels in contexts where precise models are available, such as process control, while adaptive control is better suited to systems experiencing significant and frequent parameter changes [13], [23], [24]. PDFCS strikes an optimal balance, excelling in scenarios that demand simplicity, robustness, and computational efficiency, such as motor control.

This comparative analysis underscores the distinct advantages of PDFCS over adaptive control and MPC, particularly in its simplicity, computational efficiency, and consistent performance under varying conditions. While MPC and adaptive control demonstrate strengths in specific domains, PDFCS emerges as a practical, reliable, and efficient solution for real-time applications, particularly in motor control, where a balance of performance and simplicity is critical.

4.7. Computational Complexity

One aspect that warrants attention in the implementation of the proposed PDFCS is computational complexity. As the PDFCS involves processing input variables and generating control actions based on fuzzy logic rules, it may introduce additional computational overhead compared to traditional PID controllers.

The computational complexity of the PDFCS primarily stems from two main sources: the determination of fuzzy logic rules and the execution of fuzzy inference algorithms. Designing an effective rule-base for the PDFCS requires careful consideration of system dynamics and performance objectives, which may involve extensive experimentation and tuning. Additionally, the execution of fuzzy inference algorithms to derive control actions involves computing membership functions, rule activation degrees, and defuzzification, all of which contribute to computational load.

As the size of the rule-base and the number of input variables increase, the fuzzy inference process may require additional computational time, potentially leading to delays in real-time applications. This is particularly relevant in systems with high-speed dynamics, where timely control actions are critical. The complexity of defuzzification methods, such as the COA, further contributes to processing time. To mitigate these delays, optimization strategies such as parallel processing, efficient inference algorithms, or hardware acceleration using field-programmable gate arrays (FPGAs) can be employed.

Scaling the PDFCS to handle a larger universe of discourse or more input variables increases the memory needed to store membership functions, rule-bases, and intermediate computation results. For resource-constrained systems, such as embedded controllers, this could pose a significant limitation. Techniques like rule-base compression, hierarchical rule structures, and selective simplification of membership functions can reduce memory usage without compromising performance.

While the PDFCS demonstrates significant computational benefits, practical constraints may affect its applicability in real-world systems. One of the primary challenges is ensuring real-time processing capabilities, particularly in applications with high-speed dynamics. The execution of fuzzy inference, including fuzzification, rule evaluation, and defuzzification, requires computational resources that may lead to delays if not optimized. Such delays can compromise system performance, especially in time-sensitive control systems.

System limitations, such as the computational power and memory capacity of hardware, impose significant constraints on the scalability of the PDFCS, particularly in embedded systems commonly utilized in industrial and automotive applications. These systems often lack the processing capability required to manage complex rule-bases or large sets of input variables efficiently, creating a need to balance the complexity of the fuzzy logic system with real-time performance requirements. To mitigate these challenges, several strategies can be employed. Optimizing rule-bases by reducing the number of rules and simplifying membership functions can help lower computational overhead without compromising control accuracy. Hardware acceleration, using devices such as GPUs or FPGAs, can dramatically enhance processing speeds, enabling real-time implementation. Additionally, adopting adaptive and modular designs allows the PDFCS to be structured into smaller, more flexible components, reducing the processing burden on individual modules while maintaining system performance and adaptability.

To mitigate computational complexity as a whole, additional strategies can be employed. Firstly, optimizing the rule-base structure by reducing the number of rules and simplifying rule conditions can streamline the inference process. Secondly, implementing efficient fuzzy inference algorithms and leveraging hardware acceleration techniques such as parallel computing or dedicated fuzzy logic hardware can expedite computation. Moreover, employing approximation techniques or model simplification methods may further reduce computational overhead while maintaining satisfactory performance.

By carefully balancing these trade-offs through advanced computational techniques and adaptive control strategies, the PDFCS can be effectively scaled for real-world applications, ensuring its feasibility and efficiency in diverse scenarios. These considerations provide a balanced view of the advantages and challenges associated with the proposed approach.

5. Conclusion

Servomotors serve as essential components in various applications requiring precise speed and position control. Among these, FCDCM stand out for their cost-effectiveness and stable speed regulation even in the face of torque fluctuations. Typically, these motors integrate optical encoders to monitor rotor position, with signals relayed to PID controllers for speed and position regulation. Integrating fuzzy logic into PID controllers enhances their responsiveness, minimizing oscillations between overshoot and undershoot positions and enabling accurate positioning. However, traditional approaches to designing PID FCs often overlook crucial performance criteria. Leveraging our taxonomy of design methods, we have introduced a novel approach called the PDFCS. Our analysis demonstrates a significant enhancement in accuracy, with a reduction of 2.9 seconds in rise-time, 2.0 seconds in settling-time, and a decrease of 1.9% in overshoot compared to conventional design methods. Furthermore, robustness analysis underscores the efficacy of the PDFCS, showcasing a 4.0-second improvement in rise-time, a 1.7-second enhancement in settling-time, and a reduction of 0.79% in overshoot compared to traditional methods. In summary, the proposed PDFCS represents a substantial advancement in performance and robustness, addressing the

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limitations of existing PID FC design methodologies and offering a promising avenue for more efficient and precise control across diverse applications.

6. Declarations

6.1. Author Contributions

Conceptualization: E.N.; Methodology: E.N.; Software: E.N.; Validation: E.N.; Formal Analysis: E.N.; Investigation: E.N.; Resources: E.N.; Data Curation: E.N.; Writing Original Draft Preparation: E.N.; Writing Review and Editing: E.N.; Visualization: E.N. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

The author received no financial support for the research, authorship, and/or publication of this article.

6.4. Institutional Review Board Statement

Not applicable.

6.5. Informed Consent Statement

Not applicable.

6.6. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] H. J. Ali, D. K. Shary, and H. D. Abbood, "A review of intelligent techniques-based speed control of brushless DC motor (BLDC)," *Basrah Journal for Engineering Sciences*, vol. 24, no. 1, pp. 109-119, 2024.

[2] M Cheng, J Zhou, W Qian, B Wang, C Zhao, and P Han, "Advanced electrical motors and control strategies for high-quality servo systems—a comprehensive review," *Chinese Journal of Electrical Engineering*, vol. 10, no. 1, pp. 63-85, 2024.

[3] P. Kumar, H. K. Channi, and H. Singh, "A comprehensive review of electrical motors for electric mobility," in *2024 IEEE International Conference for Women in Innovation, Technology and Entrepreneurship (ICWITE)*, vol. 2024, no. Feb., pp. 130-135, Feb. 2024.

[4] E. Natsheh and H. Ahmed, "Authentication system by facial recognition with principal component analysis and deep neural networks," *International Journal of Intelligent Systems and Applications in Engineering*, vol. 10, no. 4, pp. 179–183, 2022.

[5] E. Natsheh and M. Jabed, "Implementing artificial intelligence-based COVID-19 chatbot in the Kingdom of Bahrain," *International Journal of Intelligent Systems and Applications in Engineering*, vol. 10, no. 3, pp. 10–17, 2022.

[6] H. Ong, E. Natsheh, and T. Wan, "Routing with a density-based probabilistic algorithm for mobile ad-hoc networks," *Journal of High-Speed Networks*, vol. 18, no. 2, pp. 83-114, 2011.

[7] S. Kumar and E. Natsheh, "Multivariate fuzzy analysis for mobile ad hoc network threat detection," *International Journal of Business Data Communications and Networking (IJBDCN)*, vol. 4, no. 3, pp. 1–30, 2008.

[8] E. Natsheh, "A survey on fuzzy reasoning applications for routing protocols in wireless ad-hoc networks," *International Journal of Business Data Communications and Networking (IJBDCN)*, vol. 4, no. 2, pp. 22–37, 2008.

[9] E. Natsheh, S. Khatun, A. B. Jantan, and S. Subramaniam, "Fuzzy metric approach for route lifetime determination in wireless ad-hoc networks," *International Journal of Ad Hoc and Ubiquitous Computing*, vol. 3, no. 1, pp. 1–9, 2008.

[10] E. Natsheh, A. B. Jantan, S. Khatun, and S. Subramaniam, "Adaptive optimizing of hello messages in wireless ad-hoc networks," *International Arab Journal of Information Technology (IAJIT)*, vol. 4, no. 3, pp. 191-200, 2007.

[11] J. B. S. Freitas, L. Marquezan, P. J. D. de Oliveira Evald, E. A. G. Peñaloza, and M. M. H. Cely, "A fuzzy-based predictive PID for DC motor speed control," *International Journal of Dynamics and Control*, vol. 12, no. 1, pp. 2511-2521, 2024.

[12] P. Mohindru, "Review on PID, fuzzy and hybrid fuzzy PID controllers for controlling non-linear dynamic behaviour of chemical plants," *Artificial Intelligence Review*, vol. 57, no. 4, pp. 1-28, 2024.

[13] V. Kumarasamy, V. K. Ramasamy, G. Chandrasekaran, G. Chinnaraj, P. Sivalingam, and N. S. Kumar, "A review of integer order PID and fractional order PID controllers using optimization techniques for speed control of brushless DC motor drive," *International Journal of System Assurance Engineering and Management*, vol. 14, no. 4, pp. 1139-1150, 2023.

[14] T. Vo, X. Nguyen, M. Ha, and T. Le, "Implement fuzzy-PID controllers for trajectory tracking of an underactuated surface vessel," *International Journal of Intelligent Systems and Applications in Engineering*, vol. 11, no. 2, pp. 126–132, 2023.

[15] C. Jacob and S. T., "Predictive analytics using neuro-fuzzy model and error estimation for a dynamic process control," *International Journal of Intelligent Systems and Applications in Engineering*, vol. 12, no. 11s, pp. 30–39, 2024.

[16] K. Sasikala, R. V. R., M. V. Ramesh, J. Jeyakumar, and P. Muthukumar, "Fuzzy logic-controlled current-mode switch-mode power supply with enhanced steady-state response," *International Journal of Intelligent Systems and Applications in Engineering*, vol. 12, no. 4s, pp. 251–256, 2023.

[17] E. Natsheh and K. Buragga, "Comparison between conventional and fuzzy logic PID controllers for controlling DC motors," *International Journal of Computer Science Issues (IJCSI)*, vol. 7, no. 5, pp. 128-134, 2010.

[18] E. Natsheh and K. Buragga, "A performance comparison for various methods to design the three-term fuzzy controller," *International Journal of Computer Science and Network Security (IJCSNS)*, vol. 10, no. 5, pp. 142-151, 2010.

[19] E. Natsheh, "Designing and tuning PID fuzzy controllers for armature-controlled DC motor," *International Journal of Human and Technology Interaction (IJHaTI)*, vol. 2, no. 2, pp. 17-24, 2018.

[20] E. Natsheh, "Taxonomy of clustering methods used in fuzzy logic systems," *Journal of Telecommunication, Electronic and Computer Engineering (JTEC)*, vol. 4, no. 1, pp. 65-72, 2012.

[21] E. Natsheh, "Designing a fuzzy logic controller with a non-parametric similarity-based clustering algorithm," *Journal of Telecommunication, Electronic and Computer Engineering (JTEC)*, vol. 12, no. 4, pp. 21-29, 2020.

[22] E. Natsheh, "Dissimilarity clustering algorithm for designing the PID-like fuzzy controllers," *Journal of Information and Organizational Sciences*, vol. 45, no. 1, pp. 267-286, 2021.

[23] F. Golnaraghi and B. C. Kuo, *Automatic Control Systems*, 10th ed., McGraw-Hill Education, 2017.

[24] Schwenzer, M., Ay, M., Bergs, T. and Abel, D. "Review on model predictive control: An engineering perspective." *The International Journal of Advanced Manufacturing Technology*, vol. 117, no. 5, pp. 1327-1349, 2021.