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A novel pulse width modulation smoothing layer using sinusoidal step transition

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ABSTRACT

This paper proposes a sinusoidal step transition (SST) layer to improve the continuity of pulse width modulation (PWM) transitions in fuzzy logic (FL)-based direct current (DC) motor control. Unlike the conventional direct PWM approach, the proposed method introduces intermediate PWM values after the defuzzification stage while preserving the original fuzzy inference mechanism. Experimental results demonstrate that the proposed SST layer significantly reduces abrupt PWM variations compared with the conventional approach. Sensitivity analysis identified N = 40 as the practical operating point, achieving a smoothness index (SI) of 0.87 and providing an effective balance between PWM continuity and transition duration. The proposed modular PWM smoothing layer improves actuator-command continuity without modifying the underlying FL controller and provides a practical solution for achieving smoother actuator operation in DC motor applications.

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1. INTRODUCTION

Mechatronics, robotics, intelligent control systems, and industrial automation are widely applied in the construction of direct current (DC) motors, owing to their practical features and ability to regulate the motor's speed as required [1]-[3]. Optimized PID and fuzzy-logic control of DC motors [4], [5] and Mamdani fuzzy control for induction-motor drives [6] have been studied. Optimized fuzzy control of brushless DC (BLDC) motors has also been studied [7], and converter-integrated fuzzy control and comparative fuzzy-based speed control of DC motors have been studied [8]-[10]. Other adaptive fuzzy techniques have also been reported for BLDC and induction-motor drives [11], [12]. A wider survey on the use of fuzzy logic in uncertain and non-linear systems is also given [13].

In a conventional fuzzy-logic (FL)-based DC motor controller, the defuzzification stage produces a pulse width modulation (PWM) command that is sent to the motor driver. When the controller output changes between sampling instants, directly applying the new command can create an abrupt PWM transition. This motivates a separate conditioning stage that smooths the command transition while retaining the controller's target value. Previous studies have addressed related problems through two main directions. One direction improves fuzzy-logic controller performance. Another direction generates smoother motion using S-curve and jerk-limited trajectory profiles [14]-[17]. Related motor-drive studies have examined hybrid fuzzy/modulation strategies [18] and PWM-based approaches to improve drive operation [19]. Further work has investigated sinusoidal-jerk and jerk-continuous trajectory planning [20]-[22], while hybrid PWM has also been studied for

closed-loop motor drives [23]. These approaches address controller performance, motion generation, or modulation, whereas the present study places an independent PWM-conditioning layer after the fuzzy decision stage. Quantitative assessment specifically focused on PWM transition continuity remains the motivation for the metrics introduced in this work.

To address such drawbacks, this paper introduces a smooth PWM based on sinusoidal step transition (SST) between the FL controller and the motor driver. The proposed layer slowly evolves the FL-generated PWM target to the intermediate PWM commands without altering the fuzzy inference mechanism. Also, two quantitative parameters, the smoothness index (SI) and maximum ΔPWM per step, are proposed to quantify the continuity of PWM transitions. The effectiveness of the proposed method is validated by experimental results, showing an improvement in PWM continuity without changing the architecture of the original FL controller.

2. METHOD

The proposed control system is based on a Mamdani FL controller and an SST layer, where the sinusoidal step transition layer enhances the continuity of the PWM signal transitions before applying the output to the DC motor. There are two ultrasonic sensors, which keep measuring the distance to the object and thus keep giving the input to the FL. The PWM command is generated by the controller and then passed to the proposed SST layer to obtain the desired smooth actuator operation, which is then passed to the motor driver. Figure 1 shows an overall control procedure.

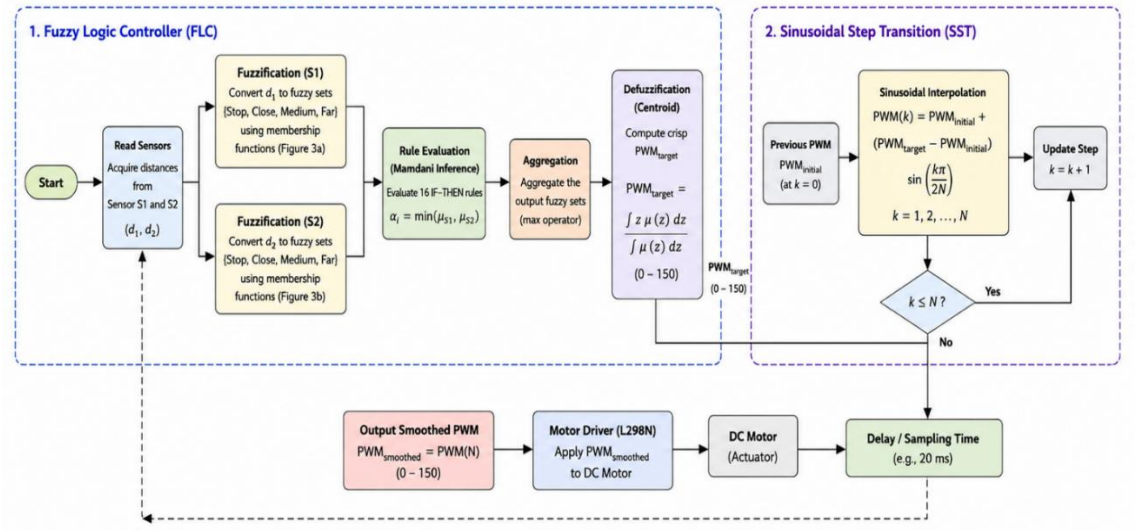


Figure 1. Proposed FL controller with the SST layer

2.1. FL controller

A Mamdani-type FL controller is adopted for its simplicity, robustness, and suitability for nonlinear DC motor control [4], [5], [8]. The distances measured by ultrasonic sensors S1 and S2 are fuzzified using four linguistic variables: stop, close, medium, and far. The controller output uses four linguistic variables: stop, low, medium, and high. Triangular membership functions are selected for their computational simplicity and embedded implementation efficiency [5], [9], [10]. The membership degree is defined by (1).

$$\mu(x) = \begin{cases} 0, & x \le a \\ \frac{x-a}{b-a}, & a < x \le b \\ \frac{c-x}{c-b}, & b < x < c \\ 0, & x \ge c \end{cases} \quad (1)$$

The a, b, and c are the lower, peak, and upper bounds of each triangular membership function, respectively. The values are set according to the membership functions of the operating ranges of sensors S1 and S2 and of the PWM output. The fuzzy inference process uses the Mamdani minimum operator to calculate the firing strengths of the rules, which are shown in (2) [4]-[6], [11].

$$\alpha_i = \min(\mu_{S1}, \mu_{S2}) \quad (2)$$

In which μ_{S1} and μ_{S2} represent membership degrees of the linguistic variables of sensors S1 and S2, respectively. The fuzzy output is aggregated and then converted to a crisp PWM output by the centroid defuzzification method due to its stable output characteristics [5]-[7], [12], as computed by (3).

$$PWMtarget = \frac{\int z\mu(z)dz}{\int \mu(z)dz} \quad (3)$$

The rule base was designed from the combinations of S1 and S2 to map the relative sensor conditions to the required PWM command. The fuzzy rule base consists of 16 IF–THEN rules defined from the combinations of S1 and S2. When both sensors indicate "Stop," the PWM output is "Stop." For S1 = stop, the PWM output varies from high to low as S2 changes from close to far. For S1 = close, the output is high for S2 = stop, close, or medium, and medium for S2 = far. For S1 = medium, the output is high for S2 = close, medium for S2 = stop, and low for S2 = far. For S1 = Far, the output is medium for S2 = close and low for S2 = stop, medium, or far. These 16 rules define the mapping from the two sensor inputs to the fuzzy PWM output.

2.2. Sinusoidal step transition

The FL controller produces a reasonable PWM signal; however, directly applying the defuzzified output to the actuator can cause sudden changes in the actuator command. To address this issue, an SST layer is introduced to gradually interpolate the PWM command before it is applied to the motor driver. The proposed transition is given by (4).

$$PWM(k) = PWMinitial + (PWMtarget - PWMinitial)\sin\left(\frac{k\pi}{2N}\right) \quad (4)$$

Where $PWMinitial$ is the value of PWM in the last step, $PWMtarget$ is the PWM value produced by the fuzzy controller, N is the number of transition steps, and k is the index of the transition. This is an interpolation to smooth the command that the actuator sends out, but at the same time, the original fuzzy control decision is kept.

2.3. Performance evaluation

This study proposes the SI as a quantitative index for PWM transition continuity performance measurement to evaluate the effectiveness of the proposed SST layer. The SI is calculated as (5).

$$SI = 1 - \frac{N|PWMtarget - PWMinitial|}{\sum_{i=1}^{N}|PWM(i+1) - PWMi|} \quad (5)$$

Where SI values closer to unity imply smoother transitions in PWM and lower command discontinuities. Along with the SI, the maximum PWM increment per transition step ($\Delta PWMmax$) is evaluated to determine the largest PWM increment in each transition.

2.4. Experimental setup

The experimental prototype is shown in Figure 2(a), while Figure 2(b) presents the monitoring interface used to observe the PWM response. The system was implemented using an Arduino Uno as the main controller, two HC-SR04 ultrasonic sensors as distance-measurement inputs, an L298N motor driver for PWM-based actuation, and a 12-V DC motor. The fuzzy logic controller generates the PWM target value, which is subsequently processed by the proposed SST layer before being transmitted to the motor driver.

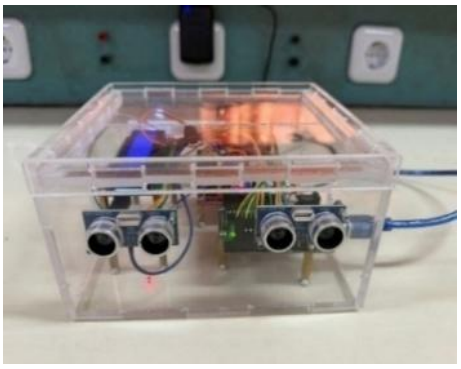
(a)  (b) 

Figure 2. Implementation: (a) experimental prototype and (b) monitoring interface

3. RESULTS AND DISCUSSION

This section assesses the suitability of the proposed SST layer for promoting PWM transition continuity in the control of a DC motor. The proposed method is first compared with the conventional direct PWM approach by analyzing the transition waveforms. Finally, a quantitative performance measure is shown, and a sensitivity analysis is performed to find the best number of transitions. Finally, the applicability of the proposed SST layer is discussed.

3.1. PWM transition analysis

The PWM transition responses of the conventional direct PWM method and the proposed SST layer are compared in Figure 3 with four PWM target values obtained by the FL controller. The typical PWM approach is to step the PWM command from the initial value to the target value in a single step, causing the input to the actuator to change abruptly. These discontinuities can generate undesirable mechanical shocks and electrical stress when the motor is running.

The SST layer, however, slowly steps through a series of intermediate PWM values to get to the target PWM value. The SST layer generates smooth and monotonic transition profiles for all PWM target values without overshoot or oscillation. Furthermore, the final PWM values are the same as those obtained in the FL controller, showing that the proposed method only changes the transition characteristics but does not change the decision of the controller. The results indicate that the SST layer effectively suppresses abrupt actuator operation variations while preserving the original fuzzy inference mechanism. Consequently, smoother PWM transitions are achieved without changing the controller output.

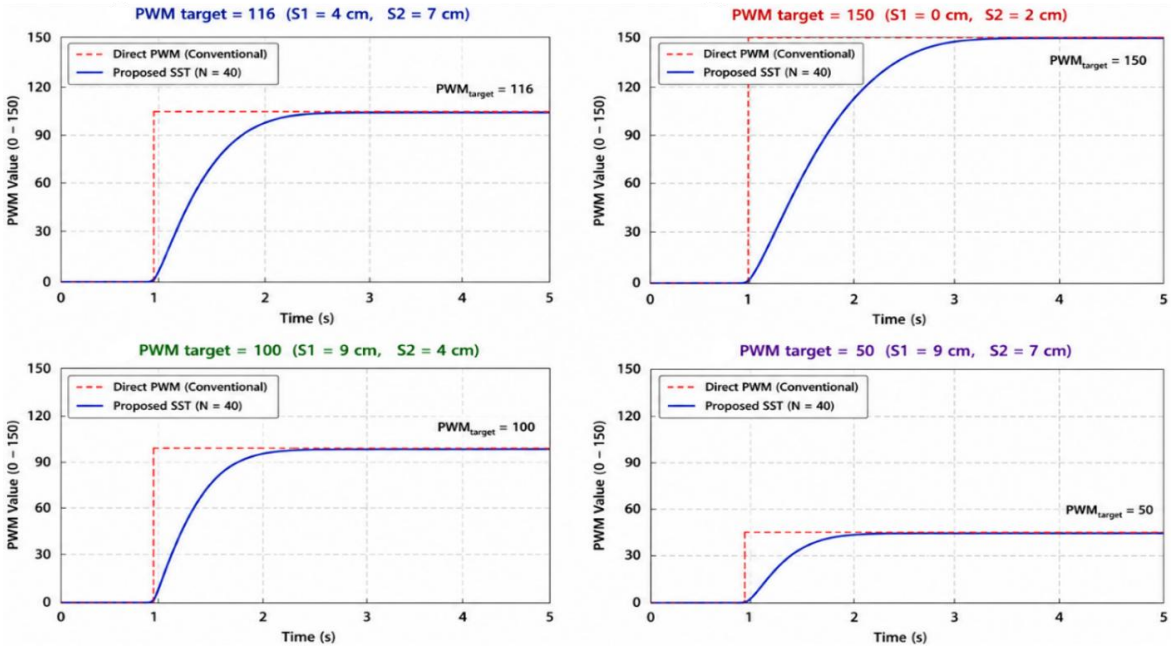


Figure 3. Comparison of PWM transitions between conventional direct PWM and the SST layer

3.2. PWM transition characteristics using the SST layer

The above-mentioned quantitative performance comparison between the conventional direct PWM method and the SST layer is summarized in Table 1. Several performance indicators are considered in the comparison. These indicators include the maximum instantaneous PWM variation and SI.

Table 1. Comparison of the conventional PWM and the SST layer

Performance metric	Conventional direct PWM	SST layer
Final PWM target	Same as FL output	Same as FL output
PWM transition	Abrupt	Smooth
Maximum ΔPWM (counts)	116	16
SI	0.00	0.87
Intermediate PWM values	No	Yes
Actuator operation	Abrupt	Smooth

The final PWM target decided by FL controller is the same for both methods (as can be seen from Table 1). In the SST layer, however, smoothed PWM values are introduced, which slowly ramp the actuator towards the desired command, as opposed to the conventional method. Therefore, the PWM variation is substantially reduced, while the same control objective is maintained. The SST layer achieves an SI of 0.87, indicating smoother PWM transitions than the conventional direct PWM method. Because of the reduced transition discontinuity, it is expected that a smoother transition in the excitation of the actuators will enable the overall continuity of the operation of the DC motor without requiring any further modification of the FL controller.

3.3. Sensitivity analysis of the transition-step number

The SST layer was evaluated with the step values of N as 10, 20, 40, 60, 80, and 100 to select an appropriate value of the transition-step number. This was done for 4 representative values of PWM (50, 100, 116, and 150) and the generated smoothness index (SI). As shown in Figure 4, the SI is always increasing with the increase in the number of transitions for all the PWM target values. The four curves show that the SST layer has similar smoothing characteristics for various operating conditions of PWM. The more transition steps there are, the greater the PWM variation will be distributed, and the more gradual the transitions will be.

The numerical values are summarized in Table 2. The improvement of the SI with N is gradual, but the transition duration is still growing. This behavior is a compromise between the smoothness of PWM transitions and the speed of the transitions. Therefore, N = 40 was selected as the practical operating point because it provides the best trade-off between PWM transition continuity and transition duration. The controller operates at this point to maintain an SI of 0.87, indicating smooth PWM transitions without adding too much delay.

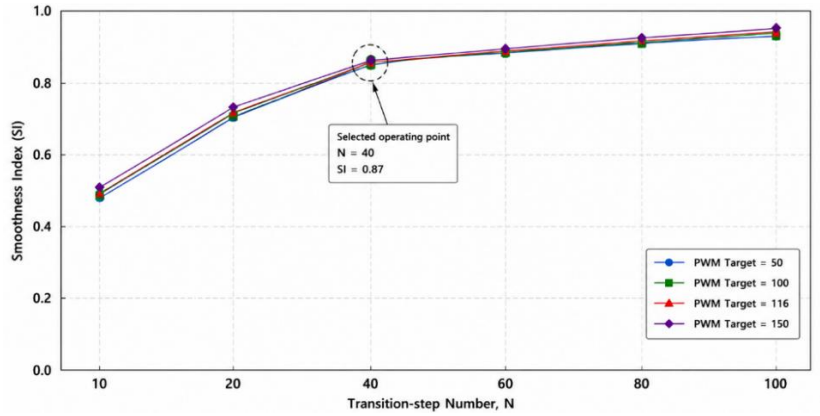


Figure 4. Sensitivity of the SI to the transition-step number for various PWM target values

Table 2. Sensitivity analysis of the transition-step number

N	SI	Maximum ΔPWM (counts)	Transition duration (ms)	Observation
10	0.50	58	10	Abrupt transition
20	0.74	31	20	Improved smoothness
40	0.87	16	40	Best trade-off
60	0.91	9	60	Slight improvement
80	0.94	6	80	Marginal improvement
100	0.96	4	100	Longer transition

3.4. Discussion

The experimental results confirm that the SST layer effectively improves PWM transition continuity while preserving the original FL controller architecture. Unlike the conventional direct PWM method, the SST layer gradually interpolates the PWM command through intermediate values before reaching the desired target, thereby reducing abrupt actuator-command variations without modifying the fuzzy membership functions, rule base, or defuzzification process. The sensitivity analysis further indicates that increasing the transition-step number improves PWM continuity but also increases the transition duration. Although higher N values produce larger SI values, the corresponding improvement becomes progressively smaller relative to the additional transition time. Therefore, N = 40 was selected as the practical operating point because it provides the best trade-off between PWM transition continuity and transition duration. At this operating point, the proposed SST achieves an SI of 0.87 while maintaining a 40-ms transition duration.

Previous studies have generally followed two different research directions. The first focuses on improving controller performance through fuzzy-based or hybrid control strategies [8]-[10]. The second focuses on smooth motion generation through S-curve and jerk-limited trajectory planning [14]-[16], alongside PWM-based motor-drive approaches [19], [23], [24]. These approaches address controller intelligence, motion continuity, or modulation within the drive. In contrast, the SST layer introduces an independent PWM-conditioning stage after the fuzzy decision, allowing the command transition to be smoothed while preserving the original controller architecture.

Another contribution of this work is the introduction of the SI together with the maximum ΔPWM per step as objective metrics for evaluating PWM transition continuity. These metrics specifically characterize changes in the actuator command between transition steps, rather than the motor speed response or trajectory-tracking performance [25]. Owing to its modular design and low computational complexity, the SST layer can be integrated into existing FL controllers implemented on low-cost embedded platforms without requiring controller redesign. Consequently, the SST layer provides a practical approach for improving actuator-command continuity while maintaining the adaptive behavior of the original FL controller.

4. CONCLUSION

This study introduced an SST layer to improve PWM transition continuity in FL-based DC motor control. Unlike the conventional direct PWM approach, the SST layer introduces intermediate PWM values after the defuzzification stage without modifying the FL controller architecture. Experimental results demonstrated that the SST layer effectively reduced abrupt PWM variations while preserving the desired control output. Sensitivity analysis identified N = 40 as the practical operating point, providing the best trade-off between PWM transition continuity and transition duration with an SI of 0.87. The proposed SST layer therefore provides a modular and lightweight approach for improving actuator-command continuity while preserving the original FL control structure. The present validation was limited to PWM transition characteristics under laboratory conditions; future work will investigate variable-load operation, motor dynamic performance, switching-frequency effects, and robustness against measurement disturbances.

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AUTHOR CONTRIBUTIONS STATEMENT

The authors confirm that all listed authors have made substantial intellectual contributions to this work in accordance with the Contributor Roles Taxonomy (CRediT).

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state that there is no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [MB], upon reasonable request.

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