DESIGN, IMPLEMENTATION AND EVALUATION OF A MULTI-INPUT FUZZY LOGIC CONTROLLER FOR CONTROL OF DC MOTOR SPEED BASED ON AMBIENT TEMPERATURE

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Abstract

The use of automatic control in the operation of engineering systems based on specified criteria should reduce the need for operator intervention, which will be extremely beneficial for the smooth operation of such systems. In these applications, fuzzy logic is a common controller. It is evident from the literature that fuzzy logic setup for single-input and multi-input has been used. However, due to the mathematical complexity of the multi-input setup, a performance comparison of the single-input and multi-input fuzzy logic setup is required. Hence, this paper presents the design and implementation of both setups for DC motor speed control in MATLAB/SIMULINK 2018b. Compares their performance using the transient and steady-state system response of the system hyperparameters (Temperature, Speed, Rate of Change, and Fuzzy control) for controlling DC motor speed. The ambient temperature change is the input for the single-input fuzzy logic control, while the ambient temperature change and its rate of change are the inputs for the multi-input fuzzy logic control. The result shows the multi-input setup outperforms the single-input setup, with fewer fluctuations in steady and transient state responses. A reduced mean squared error of 22.56, root mean square of 4.75, and an increased accuracy of approximately 97.34 % for ambient temperature ranges from 20 to 50 degrees Celsius. Therefore, when designing and implementing fuzzy logic for automatic system control, multi-input fuzzy logic should be considered.

Keywords: DC Motor, Fuzzy Logic, Automatic Control, Speed Control

Introduction

Automatic control systems are preprogrammed closed-loop control systems that do not demand operator intervention. This assumes that the process continues within the control system's typical range. An automatic control system consists of two process variables: a regulated variable and a manipulated variable. In this work, the regulated variable is the DC motor speed level, while the manipulated variable is the ambient temperature. Fuzzy logic is a common controller in these applications. The fuzzy logic concept is functionally equivalent to the human sensation and inference process (Anil *et al.*, 2019). The design process of membership functions for input and output, as well as the design engineering of fuzzy if-then rule knowledge base, are the most essential parts of fuzzy logic control system development. (Neethu *et al*., 2016). Fuzzifications of both inputs and outputs using ancillary membership functions result in a fuzzy controller's output. Based on its value a crisp input will be morphed into the various members of the linked membership functions (Anil *et al*., 2019). Fuzzy logic has been used in a variety of automatic control applications with single-input and multi-input set up in recent years. Khairudin *et. al.*, (2021) presented a twin input (temperature and distance) Fuzzy logic control for DC motor speed control using Mamdani technique. The system was simulated in MATLAB and Proteus environment and the result showed the Fuzzy logic control attained about 90 % of the DC motor desired speed. Lahlouh *et al*., (2020) proposed a Multi-Input Multi-Output (MIMO) Fuzzy Logic Controller (FLC) combined with a Proportional, Integral, Derivative (PID) controller tuned by fuzzy rules for controlling the hygro-thermal parameters (temperature and relative humidity) and contaminant gases (NH_3, CO_2) of a prototype poultry house. The performance of the proposed system was compared with the Fuzzy logic control (FLC) system and the On/Off system. The result showed that the daily weight gained by the chickens for the proposed system was found to be 97%, which is higher than that of FLC (88%) and On/Off (80%). Nassim and Abdelkader (2021) proposed a DC motor speed control system using fuzzy logic control tuned PID parameters. The input to the fuzzy logic control is the setpoint error and the derivative of the speed error. The comparison between the conventional response and the fuzzy self-tuning response was performed based on the simulation result obtained by MATLAB/SIMULINK. The proposed method achieved better speed tracking with short rise and settling times, zero overshoot, and steady-state error compared to the conventional PID controller. Atar *et. al.,* (2021) Implemented a fuzzy algorithm on a PIC 16F877A microcontroller for DC motor control. The signal error and change in error are the two inputs to the fuzzy control. The result showed that, if fuzzy-PID and fuzzy type-2 controllers are embedded in the microcontroller it can improve the response of the motor. Anil *et. al.,* (2019) proposed the speed control of a DC motor using fuzzy logic controller by PCI 6221 with MATLAB, the work involved development of a fuzzy logic controller in MATLAB Simulink environment and hardware implementation consisting of DC motor Driver and PCI 6221. The results of the experiment on the real plant demonstrate that the proposed Fuzzy Logic Controller response is very good and it is robust, faster, and flexible. Devendra *et. al.,* (2019) compared Fuzzy-PID and PID Controller for speed control of DC motor using LabVIEW. The DC motor voltage is the fuzzy input. The result show that the Fuzzy-PID preformed better compared to the PID Controller. Sukiran *et. al.,* (2018) presented the control of an air-cooling system based on fuzzy logic, the study aimed to design and build a prototype air cooling controller to control the speed of the fan according to conditions of temperature and humidity. The fuzzy input is temperature using the DHT 22 sensor.

The result shows the average accuracy for temperature testing as 3.89 % and the average humidity accuracy is 3.21 %. Ahmet and Berat (2018) presented a single input fuzzy logic control to control DC motor speed. The simulation was done with MATLAB/Simulink the result show that the fuzzy logic control minimized the error between the DC motor desired speed and the actual speed. Almatheel and Abdelrahman (2017) proposed controlling the speed of a DC motor with a PID controller and a fuzzy logic controller. The fuzzy logic controller has two inputs, one of which is the speed error and the other is the change in the speed error. The Mamdani system, which employs fuzzy sets in the subsequent part, is used by the Fuzzy logic controller. The trial-and-error method is used by the PID controller to select its parameters. PID and FLC are studied using the MATLAB / SIMULINK package programme simulation. The results show that FLC is more difficult to design than PID controller, but it is more suitable to satisfy the non-linear characteristics of DC motor. Furthermore, the results show that the fuzzy logic has the minimal transient and steady-state parameters, indicating that the FLC is more efficient and effective than the PID controller. From the literature, a fuzzy logic setup for single-input and multi-input has been used. However, due to the mathematical complexity of the multi-input setup, a performance comparison of the single-input and multi-input fuzzy logic setup is required. Hence, this paper compares the performance of a single-input and multi-input fuzzy logic control for controlling the speed of a DC motor. The design, evaluation, and performance comparison of a single-input and multi-input fuzzy logic controller equipped with a temperature sensor to control the speed of a DC motor is presented. The change in ambient temperature is the input for the single-input fuzzy logic while the change in ambient temperature and it rate of change are the inputs for the multi-input fuzzy logic control. Both setups are designed and implemented in MATLAB/SIMULINK 2018b. Using the transient and steady-state system response of the system hyperparameters (Temperature, Speed, Rate of Change, and Fuzzy control output), the performance of the multi-input fuzzy logic is compared to the single-input for the changes in ambient temperature for the control of the DC motor speed. Furthermore, the mean-square error (MSE), root mean square error (RMSE), and accuracy (ACC) were employed to compare the actual DC motor speed level with the single-input and multi-input fuzzy logic setups output DC motor speed level at various ambient temperatures.

Materials and Method

The parameters of the DC shunt motor are shown in Table 1. Equation 1 shows the mathematical model of the Shunt DC motor given by (Martins *et al.*, 2022), and Fig. 1 shows its Simulation model as a subsystem.

$$\omega(s) = \left[\frac{1}{J_m.s + B_m}\right].K_t.\left[\frac{(E_a(s) - E_b(s))}{L_a.s + R_a}\right] \quad (1)$$

Table 1. DC Motor Parameter

S/N	Parameter	Value	Unit
1	J_m	2×10^{-6}	Kgm^2
2	B_m	1.33×10^{-6}	Nms/rad
3	R_a	3.23	Ohm
4	L_a	0.0035	H
5	K_t	0.01152	Nms/A
6	K_{emf}	0.01152	V/rad/s
8	C	0.001	µF

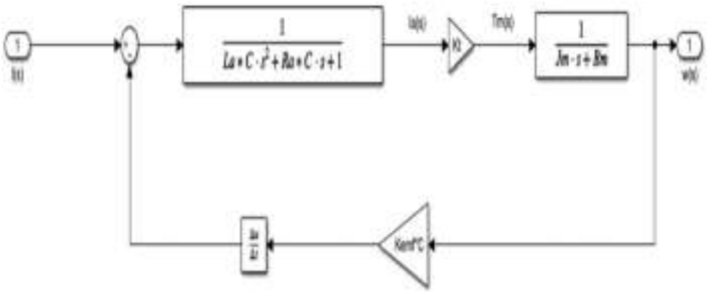

Fig. 1. Model of Equation 1 in Simulink

Fig. 2 in Simulink depicts the temperature sensor subsystem.

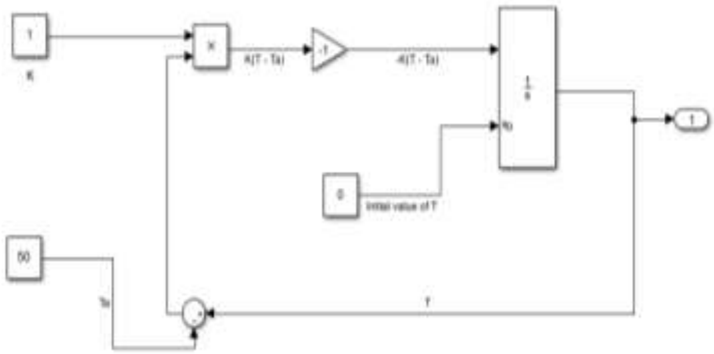

Fig. 2. Simulink temperature sensor model

The crisp temperature ranges for the first and second inputs are shown in Tables 2 and 3, respectively.

Table 2. Crisp Temperature Range for First Input

Fuzzy Variable	Membership Function used	Crisp Input Range
Very Cold	Trapezium MF	[20 20 22 24]
Cold	Triangular MF	[22 24 28]
Moderate	Triangular MF	[24 30 34]
Hot	Triangular MF	[30 38 42]
Very Hot	Trapezium MF	[38 42 50 50]

Table 3. Crisp Temperature Range for Second Input

Fuzzy Variable	Membership Function used	Crisp Input Range
Low	Trapezium MF	[0.00091 0.00096 0.0010 0.0011]
Medium	Triangular MF	[0.00101 0.00151 0.00181]
High	Trapezium MF	[0.00151 0.00201 0.0024 0.0024]

Table 4. Crisp Range for the DC Motor's fuzzy logic output speed

Fuzzy variable	Membership function used	Crisp Output Range
Very slow	Trapezium MF	[0 0 15 20]
Slow	Triangular MF	[20 45 75]
Moderate	Triangular MF	[75 125 150]
High	Triangular MF	[125 150 200]
Very high	Trapezium MF	[175 225 255 255]

Fig. 3 and 4 show the design of the membership functions for the multi-input fuzzy logic in MATLAB using ambient temperature change (first input) and rate of change in ambient temperature (second input).

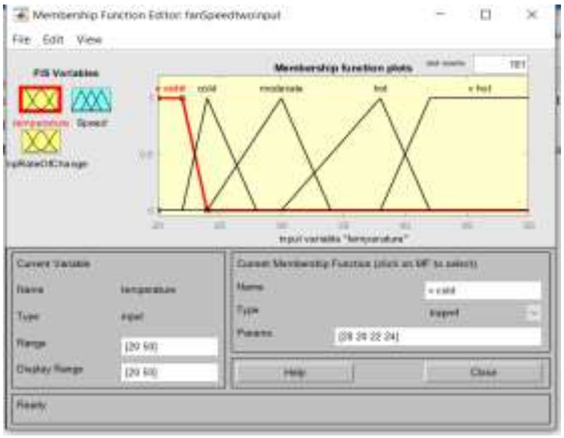

Fig. 3. First Input Membership Function

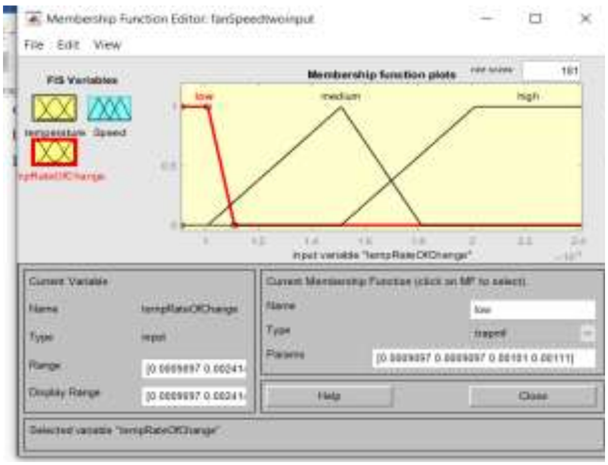

Fig. 4. Second-input membership function

Table 4 and Fig. 5 show the crisp range for the fuzzy logic output speed for the DC motor and the fuzzy logic output speed for the dc motor membership function.

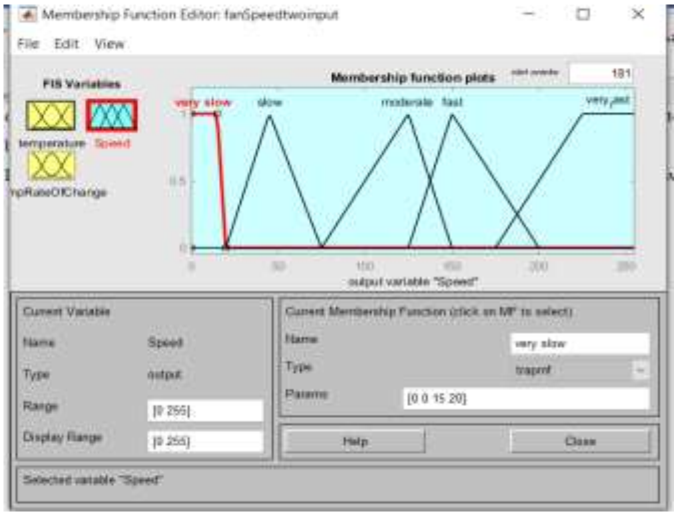

Fig. 5. Fuzzy Logic Output Speed for the DC Motor Membership Function

The rules that have been outlined in the MATLAB/fuzzy rule editor are used to design the fuzzy logic controller; the Mamdani inference method is used to create the rules. These rules are as follows;

Rule 1

If the temperature in the enclosed space is quite low (very cold) and the temperature change rate is slow, the fan speed will be quite slow.

Rule 2

If the closed space temperature is quite low (very cold) and the temperature change is moderate (medium), the fan speed will be very slow.

Rule 3

The fan speed will be slow if the temperature of the enclosed space is very low (very cold) and the rate of change of the temperature is high.

Rule 4

If the temperature in the enclosed space is low (cold) and the rate at which temperatures change is slow, the fan speed will be very slow.

Rule 5

If the temperature in the enclosed space is low (cold) and the changing rate is slow, the fan speed will be slow.

Rule 6

If the temperature in the confined space is low (cold) and the temperature change rate is fast, the fan speed will be slow.

Rule 7

The fan speed will be moderate if the temperature of the confined space is moderate (normal) and the proportion of change in the temperature is low.

Rule 8

The fan speed will be moderate if the temperature of the confined space is moderate (normal) and the proportion of temperature change is moderate.

Rule 9

If the temperature in the confined space is mild (normal) and the rate at which temperatures change is fast, the fan speed will be fast.

Rule 10

If the closed space temperature is high (hot) and the rate at which temperatures change is slow, the fan speed will be medium.

Rule 11

If the temperature inside the confined area is high (hot) and the rate at which the temperatures change is moderate, the fan speed will be high.

Rule 12

The fan speed will be fast if the temperature of the confined space is high (hot) and the proportion of change of the temperature is high.

Rule 13

If the temperature in the confined space is very high (very hot) and the temperature change proportion is slow, the fan speed will be very fast.

Rule 14

The fan speed will be very fast if the temperature of the enclosed space is very high (very hot) and the proportion of change of the temperature is moderate.

Rule 15

If the temperature in the confined space is extremely high (extremely hot) and the rate of change of the temperature is extremely fast, the fan speed will be extremely fast.

Fig. 6 depicts the Simulink implementation of the multi-input fuzzy logic design for DC motor speed control.

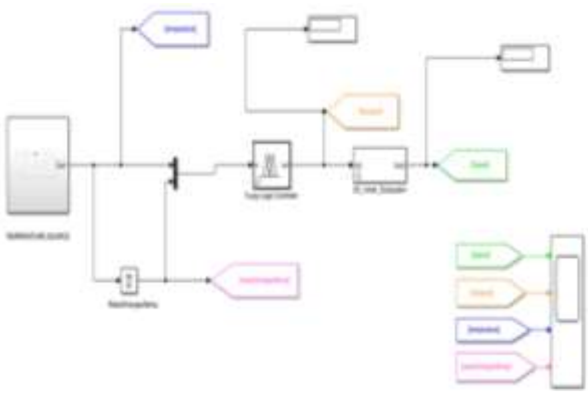

Fig. 6. Design of multi-input fuzzy logic for DC motor speed implementation.

Performance evaluation

The subject has been modelled as a problem with an automatic control system. The DC motor speed level is the controlled variable, and the first and second inputs for the designed multi-input fuzzy logic are the manipulated variables. Descriptive statistics such as MSE, RMSE, and ACC were used to evaluate the actual DC motor speed level and the fuzzy output DC motor speed level at various ambient temperatures to evaluate the designed multi-input fuzzy logic. Furthermore, using transient and steady-state system response of the system hyperparameters, the efficacy of the proposed multi-input fuzzy logic is compared to the single input of change in ambient temperature.

The mean squared error (MSE)

Determine the proximity of a regression line to a set of data points. When the MSE is low, it gives more weight to larger disparities and makes better predictions. The model is presented in Equation 2 of (Heumann and Schomaker 2017).

$$MSE = \frac{\sum_{k=i}^{N} (x_i - o_i)^2}{N} \quad (2)$$

Where x_i are the fuzzy output DC motor speed levels, o_i are the actual DC motor speed levels, and N is the number of observations available for analysis,

Root Mean Square Error (RMSE)

This is referred to as standard variability (prediction errors). The residuals quantify the distance between the data points and the regression line, while the RMSE quantifies how dispersed these residuals are. In other words, it shows how much of the data is centered on the best-fit line. The model is presented in Equation 3 of (Heumann and Schomaker 2017).

$$RMS = \sqrt{\frac{\sum_{k=i}^{N} (x_i - o_i)^2}{N}} \quad (3)$$

Where x_i are the fuzzy output DC motor speed levels, o_i are the actual DC motor speed levels, and N is the number of observations available for analysis,

Accuracy (ACC)

The distinction between the error rate and 100% is assessed here. To determine accuracy, the error rate is calculated. The error rate is calculated as the percentage of the difference between the theoretical and experimental actual DC motor speed levels divided by the theoretical DC motor speed levels (Theoretical). The model is presented in Equation 4 of (Heumann and Schomaker 2017).

$$Error\_rate = \frac{abs(Experimental - Theoretical)}{Theoretical} \times 1 \quad (4)$$

$$ACC = 100\% - Error\_rate$$

Results and Discussion

The single-input fuzzy logic, multi-input fuzzy logic, and the DC motor models (Fig. 6) were run on a computer with an Intel (R) Celeron (R) N3060 1.60 GHz processor and 4.00 GB RAM using the MATLAB/Simulink R2018b software package. The specified environment was also used to simulate the transient response, the steady-state response, and statistical analysis. The simulation results for the multi-input fuzzy logic are compared to the single-input fuzzy logic using the transient and steady-state system responses of the system hyperparameters to evaluate the multi-input fuzzy logic's performance superiority to the single-input fuzzy logic. Furthermore, at ambient temperature ranges from 20 to 50 degrees Celsius, the MSE, RMSE, and ACC were used to evaluate the actual DC motor speed level compared the DC motor output speed level for the single-input fuzzy logic setup and the multi-input fuzzy setup. The obtained results are presented in the subsections that follow.

Comparison of the Multi-Input and the Single-Input Fuzzy Logic

Figs. 7 and 8 depict the Transient Response and Steady-State Response of the system hyperparameters (Temperature, Speed, Rate of Change, and Fuzzy control) for the multi-input and single-input fuzzy logic setups for DC motor speed control over a temperature range of 20 to 50 degrees Celsius.

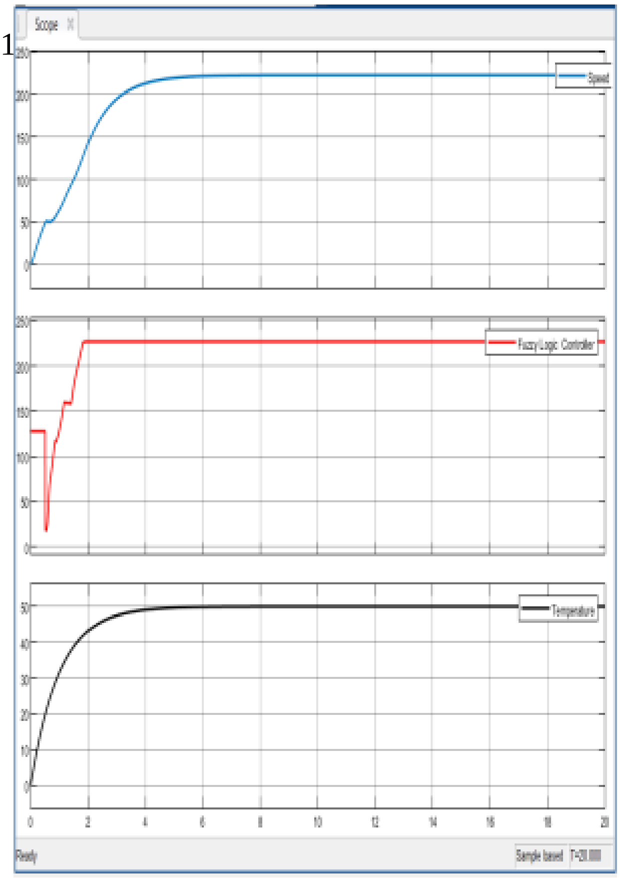

Fig. 7. Single-Input Fuzzy-Logic Transient Response and Steady-State Response of the System Hyperparameters

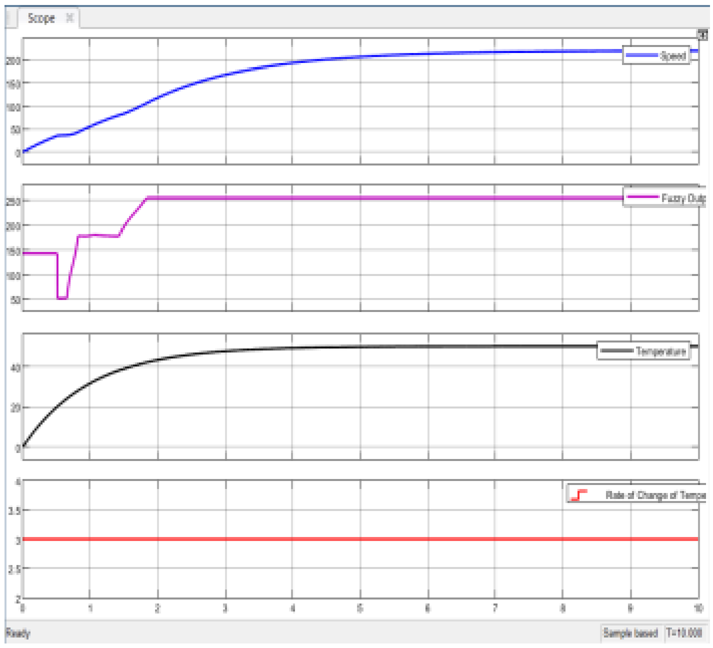

Fig. 8. Multi-Input Fuzzy-Logic Transient Response and Steady-State Response of the System Hyper Parameters

According to Figs. 7 and 8, the transient and steady-state response of the Fuzzy control output curve of a multi-input fuzzy logic setup is steadier than that of a single-input fuzzy logic setup.

Table 5 presents the actual DC motor speed level and the single-input fuzzy-output DC motor speed level at various ambient temperatures.

Table 5. Actual DC motor speed level and the single-input fuzzy output DC motor speed level

Ambient Temperature (^{0}C)	Actual DC motor speed level	Single-input fuzzy output DC motor speed level	Square error
20	19.81	20.39	0.34
21	19.81	20.39	0.34
22	19.81	20.39	0.34
23	49.89	51.36	2.16
24	72.72	74.86	4.58
25	79.75	79.75	0
26	108.7	109	0.09
27	108.9	112.1	10.24
28	109	112.2	10.24
29	109	112.2	10.24
30	109	112.2	10.24
31	120.4	123.9	12.25
32	129.5	133.3	14.44
33	140.3	144.4	16.81
34	153	157.5	20.25
35	153.6	158.7	26.01
36	154.2	158.7	20.25
37	154.4	159	21.16
38	154.6	159.1	20.25
39	184.4	189.9	30.25
40	202.2	208.2	36
41	219.3	225.8	42.25
42	239.1	246.2	50.41
43	239.1	246.2	50.41
44	239.1	246.2	50.41
45	239.1	246.2	50.41
46	239.1	246.2	50.41
47	239.1	246.2	50.41
48	239.1	246.2	50.41
49	239.1	246.2	50.41
50	239.1	246.2	50.41
			762.42

Table 6 presents the actual DC motor speed level and the multi-input fuzzy output DC motor speed level at various ambient temperatures.

Table 6. Actual DC motor speed level and the multi-input fuzzy output DC motor speed level

Ambient Temperature (^{0}C)	Rate of change (^{0}C/s)	Actual DC motor speed level	Multi-input fuzzy output DC motor speed level	Square error
20	0.0009097	8.489	8.247	0.058
21	0.0009597	8.489	8.247	0.058
22	0.00101	8.489	8.247	0.058
23	0.00106	23.79	23.11	0.46
24	0.00111	53.19	51.67	2.31
25	0.00116	86.76	84.28	2.48
26	0.00121	93.83	91.15	7.18
27	0.00126	106.3	103.3	9
28	0.00131	129.9	126.2	13.69
29	0.00136	130.3	126.6	13.69
30	0.00141	130.7	127	13.69
31	0.00146	139.9	135.9	16
32	0.00146	147.7	143.5	17.64
33	0.00151	158.8	154.3	20.25
34	0.00156	179.5	174.4	26.01
35	0.00161	179.5	174.4	26.01
36	0.00166	180	174.9	26.01
37	0.00171	179.6	174.4	30.25
38	0.00176	179.6	173.9	32.49
39	0.00181	202.5	196.7	33.64
40	0.00186	218.8	212.6	38.44
41	0.00191	235.5	228.7	46.24
42	0.00196	252.8	247.6	27.04
43	0.00201	254.9	247.6	53.29
44	0.00206	254.9	247.6	53.29
45	0.00211	255	249	36
46	0.00216	255	249	36
47	0.00221	255	249	36
48	0.00226	255	249	36
49	0.00236	255	249	36
50	0.002414	255	249	36
		5074.24		699.264

Table 7 shows the study data for MSE, RMSE, and ACC for multi-input and single-input fuzzy logic setup.

Table 7. MSE, RMSE, and ACC for fuzzy logic setups

Fuzzy Logic Setup	MSE	RMSE	Error rate	ACC (%)
Multi-Input	22.56	4.75	2.66	97.34
Single-Input	24.59	4.96	2.78	97.22

Figs. 7 and 8 show that with the multi-input fuzzy logic setup the temperature response curve attained a steady state at 3 seconds which is faster compared to the 4 seconds taken in the single-input fuzzy logic setup. Table 7 shows that the multi-input fuzzy logic setup has a lower MSE, RMSE, and higher ACC values which indicates that the change in voltage signal sent to the DC motor from the Fuzzy control is minimal for every change in temperature. Furthermore, Fig. 8 shows a gradual increase in the DC motor speed with the multi-input fuzzy logic setup which indicate that the voltage output from the Fuzzy control is stable.

Conclusion

This paper describes and compares the performance of a multi-input fuzzy logic setup for controlling the speed of a DC motor using a temperature sensor to that of a single-input fuzzy logic setup. The research looks into whether a multi-input system outperforms a single-input system in terms of the system hyperparameter's transient response and steady state response, as well as the effect on the contrast between the actual DC motor speed level and the fuzzy logic setup output DC motor speed level. The results show that the multi-input fuzzy logic configuration is more efficient and superior to the single-input fuzzy logic configuration. It has less fluctuation in the transient response and steady-state response of the system hyperparameters and reduced MSE, RMSE, and increased ACC values, indicating smooth operation of the DC motor due to a steady increase in the multi-input fuzzy setup output voltage to the DC motor in response to changes in ambient temperature. The multi-input fuzzy setup method outlined in this article has revealed its ability to control the speed of a DC motor steadily. As a result, multi-input fuzzy logic should be considered when designing and implementing fuzzy logic for automatic system control.

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Conflicts of Interest

There has been no declaration of a conflict of interest by the authors.

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