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Speed Control of DC motor for an Autonomous Wheelchair System using different Controller design strategies

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Abstract-Smart wheelchair systems have gained significant attention in recent times because of their potential in enhancing mobility and independence for people with disabilities. One of the critical components of a smart wheelchair system is the DC motor used for propulsion. The speed regulation of DC motor used in smart wheelchair system is a crucial aspect of the overall efficiency of the system. In this paper, we compare the performance of various controllers for the speed regulation of a DC motor used in a smart wheelchair system. The different controllers used in this study are Proportional-Integral-Derivative (PID) controller, Fuzzy logic controller (FLC), and Particle Swarm-optimized PID controller. A systematic simulation procedure was followed to compare the performance of each controller. The results of the study indicate that the Particle Swarm-Optimized PID controller provides the best performance in terms of speed control, with better tracking accuracy and faster response time. The study provides a comprehensive comparison of different controller types for the speed regulation of DC motor in a smart wheelchair system, which can help researchers and practitioners to choose an appropriate controller for their specific applications.

Key Words: DC motor, Speed control, Smart wheelchair system, Proportional-Integral-Derivative (PID) controller, Fuzzy logic controller (FLC), Particle Swarm Optimization (PSO).

1.INTRODUCTION

With time a lot of machines and devices have been designed and developed for the betterment of the human kind but the invention of the Smart wheelchair is a most important one. Smart, electrically powered wheelchairs have been identified as a most important tool for users suffering from mobility impairment and cognitive disabilities. So, the study of these types of wheelchairs has been recognized as an important task towards the betterment of the society [1]. The speed regulation of the DC motor is crucial for the overall performance of the smart wheelchair system, as it directly affects the user's safety, comfort, and efficiency of the system. Several control and optimization techniques have been presented in the literature for the speed regulation of the DC motor, such as the Proportional-Integral-Derivative (PID) controller, Fuzzy logic controller (FLC), Model predictive controller (MPC), Particle swarm optimization (PSO) and Ant-Colony optimization (ACO) [4]. This research work aims to compare the performance and efficiency of the three controller design strategies for the speed regulation of the DC motor used in a smart wheelchair system. These strategies are Proportional-Integral-Derivative (PID) controller, Fuzzy logic controller (FLC) and PSO-Optimized PID controller. A systematic simulation procedure was followed to evaluate the working efficiency of each controller in terms of tracking accuracy, response time, and stability. The results of the study can provide valuable insights into the selection of an appropriate controller for the speed regulation of DC motor in a smart wheelchair system.

1.1 Motivation of this Work

Accurate and efficient control is critical in every system or process. This is only possible because of the compensation provided by different controllers. Because of the low cost and easy to control, DC motors are widely used in process industries, robots, wheelchairs and in other smart devices. Control systems practically used in day today lives suffer from a lot of disabilities and problems like undesirable overshoot, vibrations, and large-settling time and stability issues. Real world processes and systems are inaccurate, non-linear and in-efficient due to which a lot of controllers are used to compensate these irregularities [9]. Classical controllers like PID controllers generally are ineffective in some cases due to which more advanced strategies like Fuzzy logic, Artificial Neural Network (ANN) technique and other optimization techniques like particle-swarm-optimization (PSO), Genetic-algorithm (GA), Ant-Colony-Optimization (ACO), Simulated-annealing (SA) etc. are used. All these techniques are effective and interesting techniques used in a lot of control problems and processes.

1.2 Contribution of this Article

In this paper our main attention is on Proportional-integral-derivative (PID) controller, Fuzzy logic controller (FLC) and PSO-optimized PID controller The focus of this research paper is to present a simple and efficient controller for the speed control of the DC motor used in a wheelchair system. Kinematical model of the motor is made in terms of the speed and angle. MATLAB/SIMULINK is then used to formulate the required Kinematical model and the different characteristics are studied by using proportional-integral-derivative (PID), Fuzzy logic Controller and particle-swarm optimized PID controller. Figure 1 depicts the schematic block diagram of DC motor with all necessary hardware components like controller, power supply, motor driver and wheelchair.

1.3 Literature Survey

The design of efficient and reliable motor drives is a very crucial aspect in various processes and applications used in industries, factories, workshops and robotics. DC motors are commonly used in many industrial purposes because of their simplicity, high efficiency, and controllability. Speed control of a DC motor is an important aspect of motor control, as it directly affects the system's response time, stability, and energy consumption. Huma khan, Shahida Khatoon et al. [2] developed a simplified model of motor using controllers such as PI , PID and LQR design strategy. In this paper LQR yields a better and efficient performance compared to PI and PID controllers. Soft-computing techniques like Fuzzy logic play a crucial role in velocity control of DC motors. Umesh Kumar Bansal et al. [3] presented a work on speed control of DC motor using Fuzzy-PID controller. Here steady state characteristics and various other characteristics like torque-speed and torque-current characteristics of the DC motor utilizing PID-Fuzzy controller are thoroughly studied. Rekha Kushwah et al. [5], K. Premkumar et al. [6] and S. Ushakumari[8] suggested a Fuzzy logic and an Adaptive Neuro-fuzzy approach to regulate the speed of brushless DC motor drive. The proposed strategy is compared with other techniques and various system parameters like Peak overshoot, Rise time, Delay time, Recovery time and Steady state characteristics has been noted and compared. Modeling and analysis of PMDC motor is done by Pragesen Pillay [9] and M.A.Jabbar [14]. Here more attention is paid on signal dynamics and motor torque characteristics. The simulation model is prepared in State Space and at every instance during on and off positions the resulting Current and Torque oscillations are measured. Optimization techniques like PSO, ANN, ACO plays an important role in optimization of different parameters in a process or plant. In this research work we used PSO control technique to optimize the parameters of PID control strategy to enhance the speed control characteristics. Particle Swarm Optimization (PSO) is a computational stochastic optimization technique based on nature inspired intelligent behavior of some animals, birds and insects like bird-flocks, ant colonies and fish schooling. It is a swarm based optimization originally formulated by Eberhart and kennedy [10]. Ruchi V. Jain et al. [12] presented PID and Fractional order PID controllers using PSO to compare the speed of DC motor. Here it was shown that Fractional order PID technique is more robust and efficient compared to normal PID controller.

2. MATHEMATICAL MODEL OF DC MOTOR

DC motors with permanent magnet use Commutator and other components like Brushes to achieve the commutation. But in case of brush-less motor, Hall Effect sensors are used to get the required mechanical commutation. In BLDC motors, stator consists of a coil and the rotor is a permanent magnet. The stator coil produces the required magnetic field that interacts with the rotor magnetic field to give the rotor a resultant rotation. The equivalent electromechanical circuit diagram of DC motor can be described by the circuit as shown in figure 1, where L_a and R_a is the equivalent Inductance and Resistance of the DC motor coil respectively. Let the Torque produced by the motor be T and terminal voltage be V. By using Kirchhoff's and Newtonian Laws the equations governing the system are as under [14]:

$$V = L\frac{di(t)}{dt} + Ri(t) + E_b(t) \qquad (1)$$

$$E_b(t) = K_b\,\omega(t) \qquad (2)$$

$$T = K_t\, i(t) \qquad (3)$$

$$T = J\frac{d\omega(t)}{dt} + B\omega(t) + T_L \qquad (4)$$

$$di(t)/dt = \frac{1}{L}(-R_a i_a(t) + V - K_b\frac{d\theta(t)}{dt}) \qquad (5)$$

$$d^2\theta(t)/\,dt^2 = \frac{1}{J}(K_t\, i_a(t) - B\frac{d\theta(t)}{dt}) \qquad (6)$$

$$E_b(t) = K_b\frac{d\theta(t)}{dt} = V - i_a(R_a + L_a) \qquad (7)$$

$$T(t) = K_t\, i_a(t) = J\,(d^2\theta(t)/\,dt^2) + B\frac{d\theta(t)}{dt} \qquad (8)$$

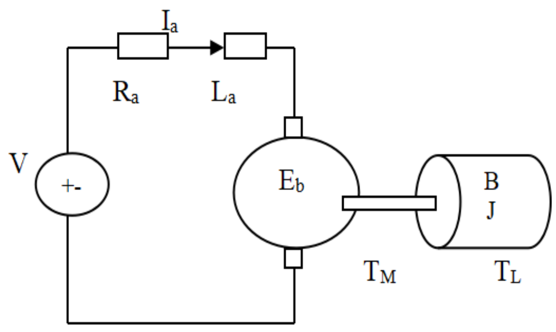


Figure.1. Equivalent circuit diagram of the DC motor

By converting the above equations into equivalent Laplace transformation and solving these equations we get the following transfer functions as shown below:

$$G_1(s) = \frac{\theta(s)}{V(s)} = \frac{Kt}{s[(R+Ls)(Js+B)+Kb]} \quad (9)$$

$$G_2(s) = \frac{\omega(s)}{V(s)} = \frac{Kt}{[(R+Ls)(Js+B)+Kb]} \quad (10)$$

Where, V is the given applied voltage, $\omega(t)$ is the rotor speed, i(t) is the armature current, E_b is the back emf, T is the torque, K_t is the motor time constant, R is the resistance, L is the inductance, J is the Inertia coefficient, B is the viscous coefficient of motor. The other specifications of the motor are summarized in the table 1.

Table 1 12 V DC Motor Specifications

Parameter	Description	Value	Units
L	Inductance	0.50	Henry
J	Inertia constant	0.02	Kg-m^2
B	Viscous constant	0.10	Nm-sec
V	Voltage	12.0	Volt
K_t	Motor time constant	0.01	Nm/A
R	Resistance	1.00	Ohm
N	Speed	3350	RPM
T	Torque	0.342	Nm
P	Power	120	Watt
I	Current	7.00	A

3. METHODOLOGY

The methodology followed in this study for comparing the performance of different controller design strategies for the speed regulation of a DC motor used in a smart wheelchair system is outlined below:

(a) System setup: A prototype smart wheelchair system with a DC motor was used for the study. The system's specifications, including the motor's voltage rating, current rating, and speed range, were noted.

(b) Control system design: The three different controllers, i.e., PID controller, FLC, and PSO-Optimized PID controller were designed and implemented using MATLAB/Simulink. The design parameters for each controller, such as gains, rules, and other parameters, were set based on the literature review and simulation results.

(c) Data analysis: The collected data was analyzed to evaluate the performance of each controller in terms of tracking accuracy, response time, and stability. The performance metrics were calculated based on the error between the desired and actual speed, the settling time, and the overshoot.

The above methodology was followed for each controller, and the results were compared to evaluate the performance of different controllers. The study provides a comprehensive comparison of different controllers for the speed control of a DC motor used in a smart wheelchair system, which can help researchers and practitioners to select an appropriate controller for their specific applications.

3.1 Proportional-Integral-Derivative (PID) Controller

This Controller is considered as one of the simple and robust controller and it works on a feedback strategy to control the given Plant or Process. It is a combination of P, I and D controller. It is a classical controller which is used to change the motor velocity by taking different values of K_p ,K_i and K_d. The summation of all these components gives the required signal that is utilized to get the optimum efficiency of the system. The basic idea behind using a PID controller for speed control of a DC motor is to use feedback from the motor's actual speed to adapt the control signal sent to the motor. The Proportional, Integral, and Derivative (PID) terms are used to adjust the control signal based on the difference between the desired speed and the actual speed. This allows for precise control of the motor's speed and ensures that it remains at the desired speed, even when external factors such as load changes or disturbances are present [12][13]. For the optimum result, the different controllers are tuned accordingly based on the given transfer function. The activating signal obtained by the PID controller is given by the following dynamic equation:

$$C(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \quad (11)$$

Transfer function of the above controller in's' domain can be simplified as:

$$C(s) = K_p + K_i/s + K_d s \quad (12)$$

Designing a PID (Proportional-Integral-Derivative) controller for the speed control of a DC motor used in a smart wheelchair system involves the following steps:

(a) DC motor modeling: Develop a mathematical model of the motor that represents its dynamic behavior. This can be done through experiments or simulations.
(b) System identification: Determine the parameters of the DC motor model, such as the resistance, inductance, and back-emf constant, through experimental tests.
(c) Controller design: Design the PID controller using the mathematical model of the DC motor. The PID

controller is made of three components: proportional, integral, and derivative. The proportional term provides a control output proportional to the error between the desired speed and the actual speed of the motor. The integral term integrates the error over time to reduce steady-state errors. The derivative term anticipates the future behavior of the system based on its current rate of change and helps to dampen oscillations.

(d) Parameter tuning: Determine the values of the PID controller gains (Kp, Ki, Kd) to get the desired performance. The tuning can be done through simulations or experimental trials.

(e) Implementation and testing: Implement the PID controller on the DC motor using a microcontroller or a dedicated motor controller. Test the system under various operating conditions to evaluate its efficiency in terms of tracking accuracy, response time, and stability.

(f) Performance evaluation: Collect data on the system's performance and evaluate the performance of the PID controller in comparison to other controller types,

3.2 Fuzzy Logic Controller (FLC)

Fuzzy logic approach mimics the human behavior takes into consideration all the required formalities that are absent in other conventional controllers like PID controller. Fuzzy logic is a very effective and efficient technique in solving different control problems. The design of an FLC used in a smart wheelchair system involves a good understanding of the system's dynamics, controller theory, and tuning methods. The FLC is a popular controller that can handle uncertainties and nonlinearities in the system, making it suitable for regulating the speed of the motor. Fuzzy logic Controller for the speed control of a DC motor used in a smart wheelchair system involves the following steps:

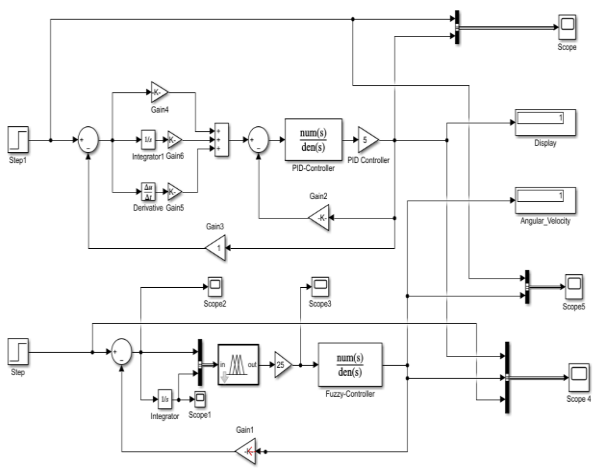


Figure 2 : Simulink representation of PID and Fuzzy logic controller with DC motor

(a) DC motor modeling: Develop a mathematical model of the motor that represents its dynamic behavior. This can be done through experiments or simulations.

(b) System-identification: Determine the parameters of the DC motor model, such as the resistance, inductance, and back-emf constant, through experimental tests.

(c) Fuzzy rule base design: Define the fuzzy sets and rules for the FLC. The different inputs to the FLC are the error and the change in error, while the output is the control signal. The fuzzy inference sets for the input and output are defined based on the system's operating range and control objectives. The rules for the FLC are formulated based on expert knowledge or experimental data.

(d) Fuzzy inference system design: Design the fuzzy inference system that maps the input variables to the output variable using the fuzzy rule base. The fuzzy inference part includes the fuzzification, rule evaluation, and defuzzification stages.

(e) Parameter tuning: Get the values of the FLC parameters, such as the membership functions and the rule base, to achieve the desired performance. The tuning can be done through simulations or experimental trials.

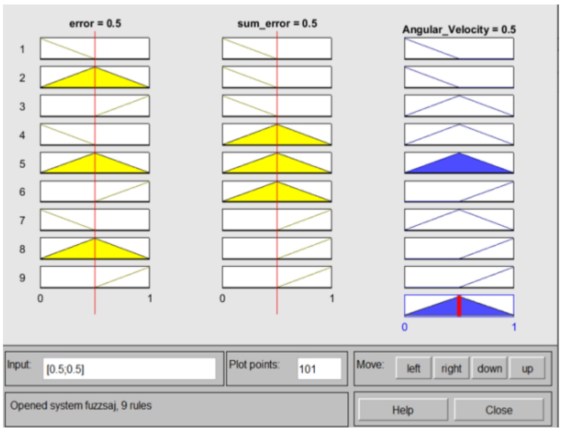
(f) Implementation and testing: Implement the FLC on the DC motor using a microcontroller or a dedicated motor controller. Test the system under various operating conditions to evaluate its efficiency in terms of tracking accuracy, response time, and stability.

(g) Performance evaluation: Collect data on the system's performance and find the performance of the FLC in comparison to other controller types, such as PID and PSO optimized PID controller, using appropriate metrics.

This section of the paper presents a rule base intelligent controller known as Fuzzy logic controller which is designed using the FIS editor. Fuzzy logic tool box is utilized to construct a rule base with the help of some linguistic rules framed in accordance with the requirements. The different variables to frame a rule base for getting the desired output are enlisted in table 2. Here a two input and one output controller is designed and the various membership functions and fuzzy rules are framed. The two inputs are error and sum_error and output is speed. Figure 3 shows the fuzzy logic interface for different rules and three dimensional view of different rules which are framed by using the toolbox.

Table 2 Rule base table for inputs and output

Error/Sum_error	CEN	CEZ	CEP
EN	N	N	Z
EZ	N	Z	P
EP	Z	P	P



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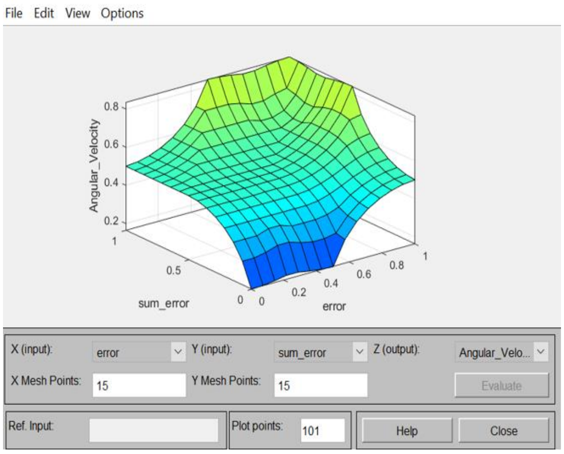

(b)

Figure 3: Fuzzy Controller interface using "Fuzzy Logic Designer" in MATLAB: (a) Fuzzy logic interface for rules; (b) Three dimensional view of Inputs and output for speed control

3.3 PSO-optimized PID controller

PSO or Particle Swarm Optimization is a metaheuristic optimization technique that is often used to optimize PID controller parameters. PSO works by simulating the characteristics of a union of particles moving through a search space and searching for the optimal parameter values that minimize a given cost function. By using PSO to optimize the PID controller parameters, it is possible to find the values that will provide the best performance for a given DC motor speed regulation application.

The PSO (Particle Swarm Optimization) algorithm is a stochastic optimization algorithm that is based on the motion of bird flocks or fish schools. It was first proposed by Kennedy and Eberhart [10] and has since been used in many optimization problems, including the optimization of PID controller to regulate the speed of a DC motor. The PSO technique starts by initializing a group of members, where each individual member represents a local best solution to the optimization problem. Each member has a position and a velocity in the search domain, and the position gives the current solution to the optimization problem. The velocity represents the direction and magnitude of the member's movement in the search space. During each iteration of the algorithm, the fitness of each particle is evaluated based on a fitness function that measures how well the particle solves the optimization problem. In the case of optimizing the PID controller parameters for the motor speed control, the fitness function measures the efficiency of the PID controller in the form of accuracy, stability, and robustness . After evaluating the fitness of each member, the member with the best fitness, is identified as the "global best" particle. The global best location is then updated to the position of the global best particle. The velocity and position of each particle are then changed using the following equations:

$$V\_ij^{t+1} = wV\_ij^{t} + c_1r_1(Pbest\_ij - X\_ij^{t}) + c_2r_2(Gbest\_j - X\_ij^{t}) \quad (13)$$

$$X\_ij^{t+1} = X\_ij^{t} + V\_ij^{t+1} \quad (14)$$

where V_ij is the velocity of member i in dimension j, w is the inertia weight, c_1 and c_2 are acceleration coefficients, r_1 and r_2 are random numbers, Pbest_ij is the best position of member i in dimension j, Gbest_j is the global best position in dimension j, and X_ij is the current position of particle i in dimension j. The PSO algorithm continues for a certain number of iterations or until a stopping criterion is fulfilled.The working of PSO-Optimized PID controller is executed by the following steps:

Step 1. The parameters of the technique like maximum number of iterations ($iter_{max}$), number of generations, swarm size, minimum inertia weight (w_{min}), maximum inertia weight (w_{max}).

Step 2. The inertia weight is calculated as :

$$w = w_{max} - (w_{max} - w_{min}) / iter_{max}$$

Step 3. The values of K_p, K_d and K_i are initialized with a certain optimum range.

Step 4. The fitness of each agent is evaluated based on Integral of square error (ISE) parameter and is given as:

$$ISE = \int_0^{\infty} e(t)^2 dt$$

Step 5. The personal-best, Pbest and global-best, Gbest of particles are evaluated based on fitness function counted in step 4.

Step 6. The velocity and position of the particles are updated according to equations given in 13 and 14.

Step 7. The steps from 2 to 6 are repeated until a termination criterion is met.

4. RESULTS AND DISCUSSIONS

The performance of the DC motor speed control can be evaluated using several performance metrics. These metrics are used to assess the accuracy, stability, and robustness of the controller, as well as its potential to respond to various operating conditions and disturbances. The following are some of the common performance metrics used to evaluate the PSO optimized PID controller for motor speed control

(a) Steady-state error: This metric measure the difference between the desired and the actual speed of the motor after the controller has reached a steady-state condition. A smaller steady-state error indicates better performance.
(b) Rise time: This metric measure the time it takes for the motor to reach 90% of the desired speed from the initial state. A shorter rise time indicates faster response and better performance.
(c) Settling time: This metric measure the time it takes for the motor to settle to within a specified range of the desired speed after reaching the steady-state condition. A shorter settling time indicates better performance.
(d) Overshoot: This metric measures the extent to which the motor speed overshoots the desired speed before settling to the steady-state condition. A smaller overshoot indicates better performance.
(e) Robustness: This metric measures the ability of the controller to maintain stable and accurate speed control in the presence of disturbances or variations in the system parameters. A more robust controller can handle a wider range of operating conditions and disturbances.

These performance metrics can be utilized to compare the working efficiency of different controllers or to optimize the PID controller parameters using the PSO algorithm. By evaluating the performance of the different controllers using these metrics, researchers can assess the effectiveness of the different controllers and PSO optimization technique and its ability to improve the performance of the DC motor speed characteristics.

The experimental or simulation results of the different controllers and PSO optimized PID controller can be represented in various forms, including graphs, tables, and charts. These results can be used to demonstrate the effectiveness of the different controllers and PSO algorithm in optimizing the PID controller parameters and improving the performance of the motor speed control system. A step response graph can be used to illustrate the performance of the different controllers and PSO optimized PID controller under a step response in the desired speed. The step response graph shows how the actual speed of the motor responds to a step change in the desired speed. The graph shows the actual speed of the motor as it responds to the change, and can highlight the steady-state error, rise time, settling time, and peak overshoot of the controller.

The PSO algorithm is a prolific optimization technique that can be used to optimize the PID controller parameters used in different applications. The algorithm works by simulating the behavior of particles moving through a search space and searching for the optimal parameter values that minimize a given fitness function. The PSO algorithm has numerous advantages over other optimization types. It is easy to implement, computationally efficient, and can handle non-linear and multi-objective optimization problems. Additionally, PSO can avoid getting stuck in local optima, which can be a common problem in gradient-based optimization techniques. In the context of motor speed regulation, the PSO algorithm can be used to optimize the PID controller parameters to achieve better performance compared to manual tuning or other optimization techniques. The PSO optimized PID controller can provide accurate and stable control of the motor speed, as well as robustness to external disturbances or variations in the system parameters.

PID controller is one of the versatile controller used to control the speed of motors. Without using the controller the open loop and closed loop responses have totally undesirable transient and steady-state characteristics. By using the PI controller the steady-state error is minimized but there is considerable error in other parameters. PID and Fuzzy logic controllers makes the desired response smooth and reduces all the drawbacks which are present in P and PI controller.The complete analysis shows that the PSO optimized PID controller has better performance as compared to other controllers which is clearly depicted from the given responses. From the design constraint point of view as we increase the value of K_p the oscillatory response of the system increases and if it is decreased settling time limit will not be in a designed range. Figure 4 shows the open-loop, closed-loop, PID and Fuzzy-logic controller responses of DC motor. Figure 5 shows the comparative step responses of different configurations using PID and Closed-loop response, Fuzzy-logic and Closed-loop response, PID and Fuzzy-logic response, and PID, Fuzzy-logic and Closed-loop responses. Figure 6 shows the step responses of DC motor using PSO-Optimized PID controller. From all these characteristics it is clear that PID and PSO-Optimized PID controller shows better response. Overall the use of PSO-Optimized PID controller shows better responses with good tracking accuracy, steady state error and better rise time and settling time which is highlighted in table 3.

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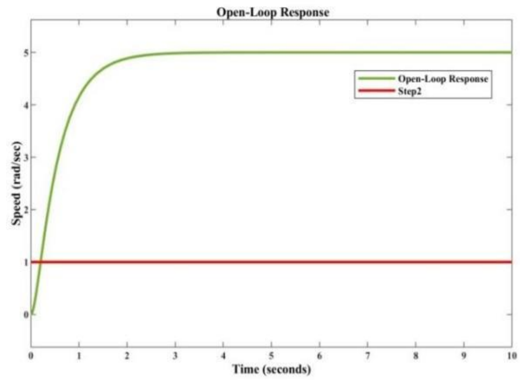

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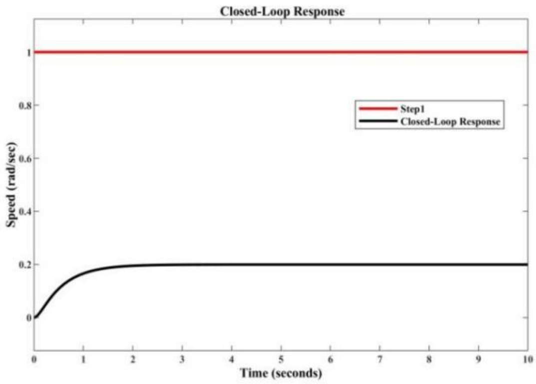

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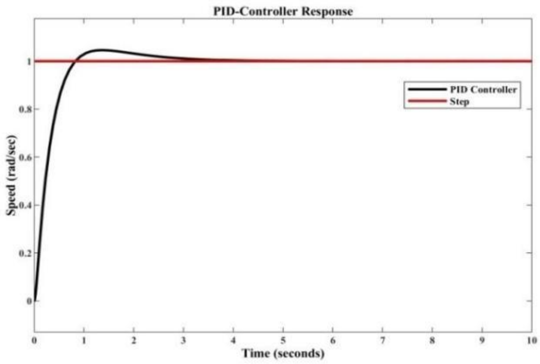

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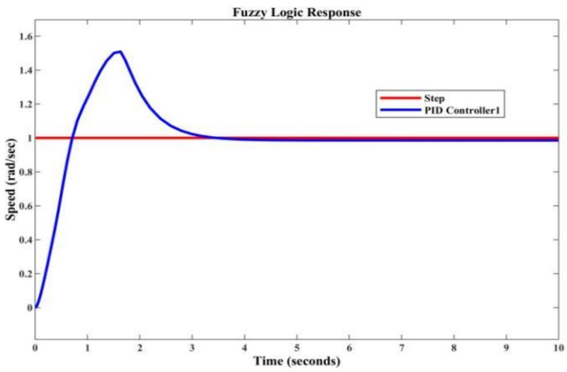

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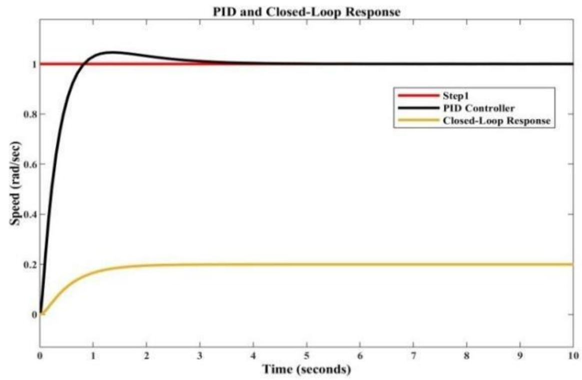
Figure 4: Step response of different configurations: (a) Open-loop response; (b) Closed-loop response; (c) PID controller response; (d) Fuzzy-logic response



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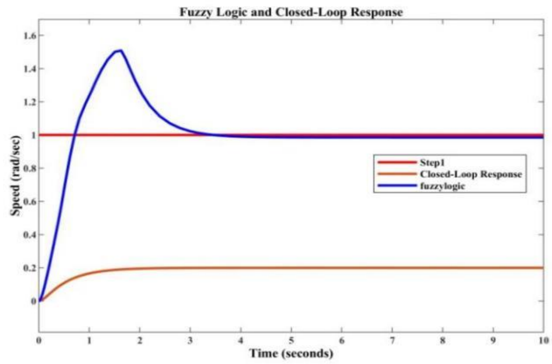

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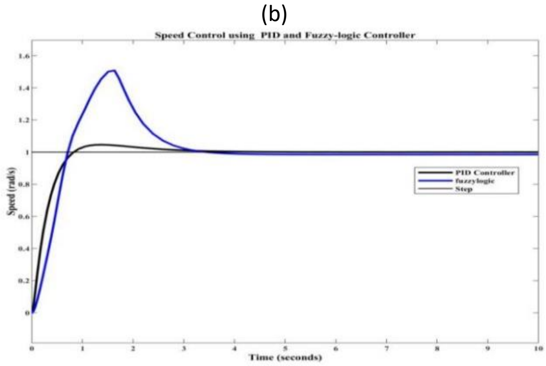

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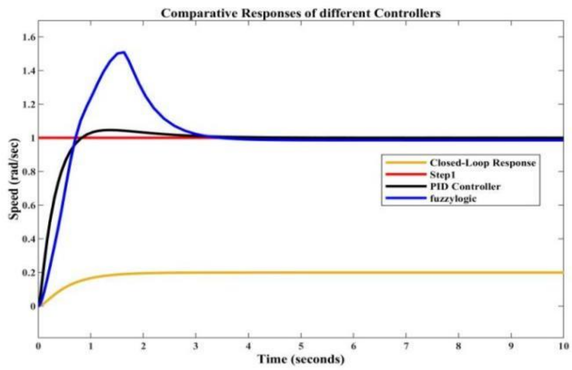

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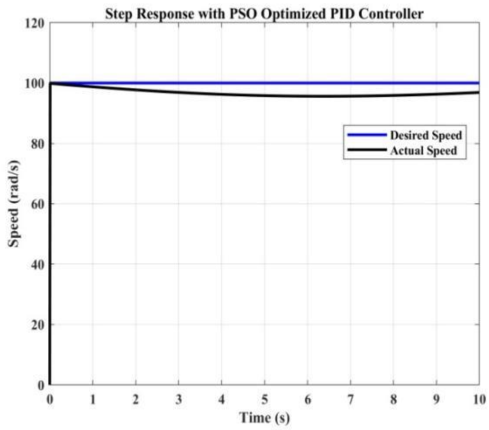
Figure 5: Comparative step responses of different configurations: (a) PID and Closed-loop response; (b) Fuzzy-logic and Closed-loop response; (c) PID and Fuzzy-logic response; (d) PID, Fuzzy-logic and Closed-loop response.



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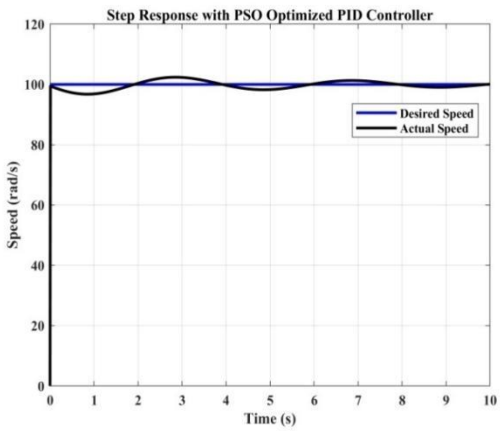

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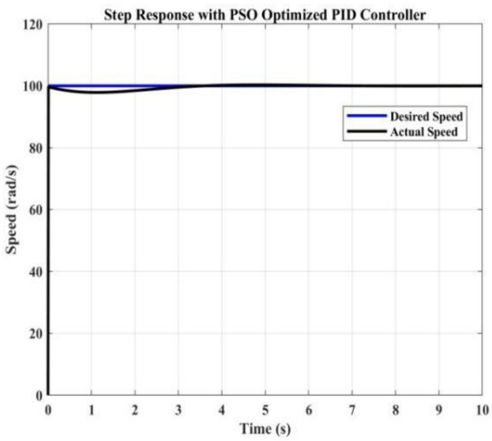

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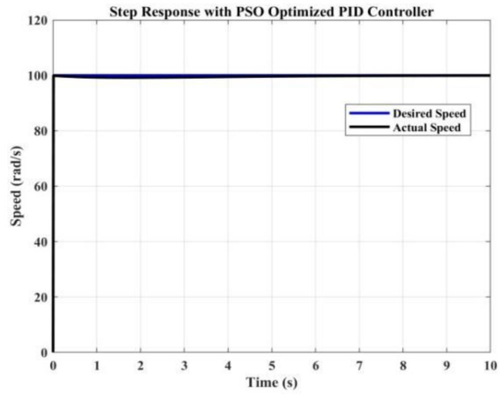

(d)

Figure 6: Step response by using PSO-Optimized PID controller with $c_1 = c_2 = 1.5$: (a) Response for swarm size 20 and maximum iteration 50,w =0.8, $r_1=r_2=0.8$; (b) Response for swarm size 30 and maximum iteration 80, w =0.8, $r_1=r_2=0.7$; (c) Response for swarm size 50 and maximum iteration 100, w =0.8, $r_1=r_2=0.6$; (d) Response for swarm size 80 and maximum iteration 100, w =0.8, $r_1=r_2=0.9$.

Table 3 Comparative Analysis of different Controllers

Controller Type	Settling Time (s)	Rise-Time(s)	Peak-Overshoot (%)	Steady-state error (%)
Open-loop	Infinite	0.25	0	500
Closed-loop	Infinite	1.8	0	800
PID	2.8	0.5	8	0
Fuzzy	1.9	0.6	50	0
PSO-PID	0	0	0	0

5. CONCLUSIONS

The kinematical model of the motor is simplified and modified using different controllers like PID, Fuzzy and PSO-Optimized PID controller. To improve the working efficiency, different parameters of the controller are varied and an optimum performance is found out. Open loop system and closed loop system give totally undesired responses with large steady-state error, delay time and settling time. These characteristics are modified using the PID, Fuzzy logic and PSO-Optimized PID controller. Further fuzzy logic controller is added individually and also with PID controller for the relative performance. After comparing the responses as shown in figures above, PSO-Optimized PID controller gave better performance in terms of robustness, tracking accuracy, stability, undesirable overshoots and delay times as compared to all other controllers. Future work involves Model Predictive Control (MPC), Artificial Neural network (ANN) and GA-

Optimized PID controller approaches. From the robustness point of view, we have to include more number of plots, observations and tables for the better understanding and comparison of different strategies. Overall, the PSO optimized PID controller for DC motor speed control is a promising research area that can lead to improved performance and efficiency in various industrial and robotic applications.

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