

Research Article

Design Kinematics and Speed Control of Autonomous Mobility System Using Intelligent Controller Design Strategies

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Abstract

Independent mobility and freedom is necessary for every individual in this world. Mobility of individuals with disabilities is often limited which can lead to a reduced quality of life. In this context, Smart mobility system is an important concept in this field of technology that can ease the life of such individuals suffering from different kinds of disorders. Smart wheelchairs have been developed to provide independent mobility to individuals with disabilities but their working performance depends mainly on the effectiveness of their kinematics and different controllers for regulating the speed of the system. The objective of this research work is to design and control the motion of autonomous mobility system that is capable of providing independent mobility to individuals suffering from different types of disabilities. This paper proposes the use of three controllers-Proportional Integral Derivative (PID), Fuzzy Logic controller (FLC) and a Particle Swarm Optimization (PSO) optimized PID controller to achieve the desired and precise motion of the system. Mathematical modelling is done by implementing different kinematic equations and the results are verified by using MATLAB software. The proposed controllers are evaluated and compared based on their performance in terms of steady state error, peak overshoot, settling time and rise time.

Keywords

Smart Wheelchair, Speed Control, PID Controller, Fuzzy Controller, PSO Optimization, BLDC

1. Introduction

Independent mobility is an important and critical factor for every individual in this world. Smart autonomous wheelchair systems are becoming an important tool or mobility assistant in the field of Assistive technology as they provide independent mobility to individuals suffering from different types of

disorders which hamper their normal motion. Smart wheelchair systems have been developed to help these individuals who are restricted by body movement [2, 4, 5]. Since control and coordination of different units of an autonomous mobility system is important, so a controller is designed for this purpose. The performance of these mobility aids also depends on

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the effectiveness of speed control system and system kinematics [6-8, 11]. Smart and autonomous wheelchairs have the potential to move and navigate through various environments and execute various tasks with the help of sensors, IoT technology and manipulator arms [3, 10]. The design and implementation of a smart autonomous wheelchair system requires the integration of different units such as the mechanical chassis, electrical system, sensor technology and control unit. There are a lot of traditional and intelligent control strategies and optimization techniques like PID, LQR, Fuzzy logic, PSO, GA, ACO etc. which can be used for motion control and trajectory tracking of autonomous agents like mobile robots and smart wheelchair systems [9, 12, 14, 32, 41]. Different types of control strategies have different benefits and weaknesses and the choice of control strategy drastically upgrade the operational performance of the mobility system. The control unit used in smart wheelchair system is an essential part of the system and can drastically enhance the motion of the system and user experience [40, 43, 44]. The motivation of this research work lies in upgrading the design and velocity control of smart wheelchair systems which systematically change the lives of people with disabilities or limited mobility. In doing so, our goal is to contribute to the advancement of smarter, safer and more user-friendly wheelchair systems.

The proposed work aims to design and control the precise motion of a smart wheelchair system by using a PID, Fuzzy and a PSO optimized PID controller and to select a suitable control strategy for the system. This study on Assistive technology can be used to improve and upgrade the design and velocity control of the smart wheelchair leading to increased comfort, safety, control overall user experience. The working performance of these control strategies is assessed by using various control parameters. Specifically, the goals of this research work are:

- 1) To design a kinematics and speed control system for a smart wheelchair.
- 2) To design and implement three different controllers (PID, fuzzy logic and PSO-optimized PID) for the motion control of the system.
- 3) To assess the working performance of the above techniques based on tracking accuracy, settling time, rise time and peak overshoot.
- 4) To determine the most suitable controller for the mobility system based on the results of the comparison.
- 5) To offer insights into the strengths and weaknesses inherent in each controller and suggest areas for future research.

2. Literature Review

A lot of work has been done in the research and development of smart and autonomous wheelchair systems for the people suffering from certain disorders and diseases which can hamper their daily normal motion. A detachable electric wheelchair is designed and controlled from a conventional

wheelchair using two omni-wheel units for driving [3]. Here a driving test is conducted according to the proposed algorithm and is verified through statistical data. A two wheeled robotic wheelchair is not always stable due to external disturbances and rough terrains. To avoid these disturbances, a stability and direction controlled wheelchair is proposed by Mostafa Nikpour et al. [9]. Here a pendulum type movable mechanism is introduced to produce necessary control actions. Luis Montesano et al. describes and evaluates an intelligent wheelchair system for the people suffering from cerebral-palsy which is one of the disorders affecting normal functioning of the human body [10]. The proposed wheelchair can automatically navigate and avoid obstacles even in unknown and cluttered environments. There are a large number of controllers and strategies which are used for motion planning of smart autonomous robots and wheelchairs such as proportional-integral-derivative (PID) controller [1, 26, 27], Fuzzy logic controller (FLC) [11-13], Artificial Neural Networks (ANNs) [41], Artificial Potential Field (APF) [42], Particle swarm optimization (PSO) [45]. The PID controller stands out as the simplest and most robust option for path tracking and speed control in robots and wheelchairs. Recently the design and motion control of a differential drive type mobile robot is proposed by Shahida khatoon et al. in which design and speed of mobile robot are achieved by using PID controller [14]. Here the tuning of PID controller is done manually to get the desired response. K Ibraheem et al. introduced the utilization of a fractional order PID controller for an autonomous wheeled mobile robot to control the speed [27]. Here, a comparison is conducted between a neural network-based controller and a PID control strategy for the path planning of the autonomous robot. Fuzzy logic controllers (FLCs) represent a type of control system utilized in engineering and computer science [18-20]. Fuzzy logic pertains to a mathematical system addressing uncertainty and imprecision. There are many advantages of using fuzzy logic as it is easy to understand, human friendly, flexible and adaptive [21, 24]. A fuzzy logic navigation controller is implemented by Mario Rojas et al. in which obstacle avoidance controller is proposed based on fuzzy logic [11]. Iztok Spacapan et al. proposes a computer simulation of wheelchair used for navigation in which fuzzy logic is used to navigate and avoid obstacles in its path [12]. The concept of differential drive is very important in designing the wheeled robots and wheelchairs. Razif Rashid et al. introduced a differential drive type mobile robot, incorporating a kinematic model and system controller utilizing fuzzy logic [13]. A low-cost design is presented by V Sankardass et al. in which direction and speed control of wheelchair is performed using ATmega 328P microprocessor [17]. Optimization techniques are commonly used in optimum path following of robots and wheelchairs to help them navigate efficiently and safely through complex environments. Different optimization strategies are employed in control and robotics including Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Ant Colony Optimization (ACO), Grey Wolf Optimization

(GWO), Differential Evolution, Simulated Annealing etc. These optimization algorithms take care of various factors like vehicle's current location, velocity and acceleration as well as any obstacles present in the surrounding to estimate the optimal trajectory for the system. Ameer L. Saleh et al. proposed a PSO based fractional order PID control strategy for a mobile robot in obtaining optimal path planning in different environments [28]. Here the optimized controller is used for velocity and direction control of the system simulated in MATLAB. A two wheeled stabilization control for a robot is proposed using Fuzzy logic controller (FLC) integrated with PSO technique [35]. The working of this system is based on an inverted pendulum type model and its mathematical modeling is done using Euler Lagrange equations simulated in MATLAB. Jinglun Yu et al. proposes the path planning of mobile robot integrated with Artificial Neural Networks (ANNs) and Hierarchical Reinforcement Learning (HRL) [41]. In this research work the proposed technique is compared with other algorithms for path planning and an optimum algorithm system was tested in different environments to prove the working of the proposed learning algorithm. Wei Yu et al. presented an experimental demonstration for dynamic behavior of a skid free vehicle in which dynamic verification of motion is done in general plane and in linear 3-D motion [25]. Combination of soft computing and optimization techniques like Fuzzy-PID and PSO-optimized PID control strategies play a crucial role in effective path planning and motion planning in control and robotics field [39]. Speed control of a unicycle type mobile robot is proposed by Norhay et al. in which a PSO-PID controller is used to find the gains of the controller for efficient response [27]. Moveh Samuel et al. assessed the performance of a Fuzzy-PID type control mechanism for street recognition [37]. Here a vision based Fuzzy-PID control technique is proposed for the simulation of a single-track vehicle. Trajectory tracking and velocity control of wheeled mobile robots and wheelchairs is an important feature in control system and robotics. Turki Y. Abdalla et al. introduced a PSO based artificial field potential approach with intelligent fuzzy system for path tracking and trajectory control of wheeled robot system [42]. Incorporating a combination of these techniques enhances the working performance and efficiency of the mobile robot in both path navigation and trajectory tracking.

The research paper is structured as follows: Literature review about the paper is presented in section II. In Section III, a detailed overview of the mathematical modeling of the smart wheelchair system is provided. In Section IV, we discuss the design and implementation of each control strategy in detail. In Section V, we present the simulation environment and results obtained from the simulations, including a comparison of the performance of the controllers and analysis of the results. Section VI tells us about the limitations of the present work and future work. Finally, we provide our conclusions in Section VII.

3. Mathematical Modeling of the Smart Mobility System

The mathematical modeling of the smart mobility system is based on a differential drive system where the two wheels are independently controlled by two brush-less DC motors. In a differential drive system, the motion and hence the velocity of the system is controlled by the difference of speeds of the two wheels. Two castor wheels are also provided in front of the wheelchair for proper balance and smooth motion control. The mathematical equations describe the relationship between the linear, angular and wheel velocities of the mobility system. The kinematic model of the proposed system is based on an assumption that the wheels are rolling in forward motion without lateral slippage and the resulting equations are highly coupled and non-linear. Figure 1 shows the general block diagram of smart wheelchair system which includes the wheelchair chassis, battery, controller, motors and other important things.

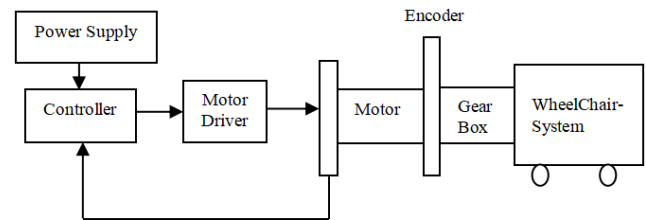


Figure 1. Major components of wheelchair system.

3.1. Kinematics of Smart Wheelchair System

The kinematic modeling of the proposed wheelchair system entails analyzing the geometric relationships that govern motion, accounting for all kinematic forces acting on the system. Figure 2 describes the kinematics of the proposed mobility system with two driving and two castor wheels to ensure the wheelchair's proper balance and control. The two separate motors connected to the two wheels have been used to control the velocity of the wheelchair system. In this context, we assume that the proposed system is rigid and moves within a horizontal plane. In Figure 2, L and C_m represent the width and the center of mass of the wheelchair system respectively. Point 'a' is positioned midway between the two wheels, and 's' denotes the distance between points 'a' and ' C_m '. The frame (O, X_g, Y_g) serves as the global frame of reference, while (O, x_m, y_m) is the dynamic frame of the proposed system. The orientation of the system is represented by θ and the three parameters (x_m, y_m, θ) define the initial orientation of the wheelchair system, given as: [15, 16, 22, 23].

$$g = \begin{bmatrix} x \\ y \\ \theta \end{bmatrix} \quad (1)$$

The proposed model of the system is based on non-holonomic constraint which means that the system will roll smoothly without slippage in sideways and this is written by the given constraint equation as shown in equation (2).

$$\dot{y} \cos \theta - \dot{x} \sin \theta = 0 \quad (2)$$

Following are the equations which describe the motion of the proposed system:

$$v = \omega r_w \quad (3)$$

$$v_R = \omega_R r_w \quad (5)$$

$$v_L = \omega_L r_w \quad (3)$$

$$\omega = \frac{v_R - v_L}{L} \quad (6)$$

$$v = \frac{v_R + v_L}{2} \quad (7)$$

The equations (6) and (7) can be put in vector matrix as:

$$\begin{bmatrix} v \\ \omega \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{L} & -\frac{1}{L} \end{bmatrix} \begin{bmatrix} v_R \\ v_L \end{bmatrix} \quad (8)$$

The kinematic equations of the proposed system can be written in matrix form as given below:

$$\dot{g} = \begin{bmatrix} x' \\ y' \\ \theta' \end{bmatrix} = \begin{bmatrix} \cos \theta & 0 \\ \sin \theta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix} \quad (9)$$

Equations (4) to (9) can also be written as:

$$\dot{x} = \frac{r_w}{2} (\omega_R + \omega_L) \cos \theta \quad (10)$$

$$\dot{y} = \frac{r_w}{2} (\omega_R + \omega_L) \sin \theta \quad (11)$$

$$\dot{\theta} = \frac{r_w}{2} (\omega_R - \omega_L) \quad (12)$$

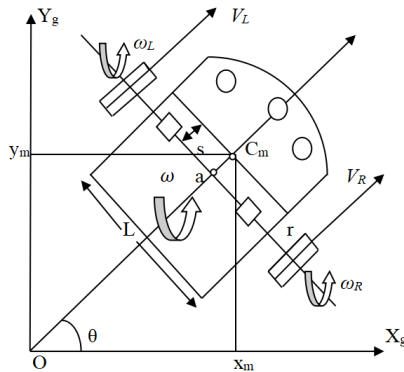


Figure 2. Kinematic and Dynamic model of the smart mobility system.

Finally, the kinematic model of the proposed system is derived by combining all the above equations and expressed in matrix form as follows:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \frac{r_w}{2} \cos \theta & \frac{r_w}{2} \cos \theta \\ \frac{r_w}{2} \sin \theta & \frac{r_w}{2} \sin \theta \\ \frac{1}{L} & -\frac{1}{L} \end{bmatrix} \begin{bmatrix} \omega_R \\ \omega_L \end{bmatrix} \quad (13)$$

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \frac{1}{2} \cos \theta & \frac{1}{2} \cos \theta \\ \frac{1}{2} \sin \theta & \frac{1}{2} \sin \theta \\ \frac{1}{L} & -\frac{1}{L} \end{bmatrix} \begin{bmatrix} v_R \\ v_L \end{bmatrix} \quad (14)$$

From Figure 2, the important parameters of the kinematic model are given as:

- v : Total Linear velocity of the system (m)
- ω : Total Angular velocity of the system (rad/s)
- r_w : Radius of wheel (m)
- v_R : Right wheel velocity (m)
- v_L : Left wheel velocity (m)
- ω_R : Angular velocity of Right wheel (rad/s)
- ω_L : Angular velocity of Left wheel (rad/s)

3.2. Kinematics of Smart Wheelchair System

The dynamic model of the wheelchair system is acquired by the knowledge of the different physical laws that govern the path of the wheelchair system like electrical and mechanical forces, friction etc. The kinematic and dynamic model of the proposed mobility system, as depicted in Figure 2, features two driving wheels independently controlled by two DC motors. The state space representation of the proposed system is given by $X = [V \ \theta \ \dot{\theta}]^T$, where the manipulated input variable is $G = [G_R \ G_L]^T$, and the output variable is represented as $Y = [V \ \theta]^T$. From the above state variable matrices, we obtain the state space equations as given below:

$$\dot{X} = AX + BG \quad (15)$$

$$Y = CX \quad (16)$$

A, B and C are state matrices defined as:

$$A = \begin{bmatrix} a & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & b \end{bmatrix}, B = \begin{bmatrix} c & c \\ 0 & 0 \\ d & -d \end{bmatrix}, C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \text{ and } a = \frac{-2C}{Mr_w^2 + 2I_\omega}, b = \frac{-2CL^2}{I_v r_w^2 + 2I_\omega L^2},$$

$$c = \frac{Kr}{Mr_w^2 + 2I_\omega}, d = \frac{KrL}{I_v r_w^2 + 2I_\omega L^2}$$

The velocity and the heading of the wheelchair are changed by manipulating the torques of the right wheel (G_R) and the left

wheel (G_1). The various parameters that are used in this dynamic model are tabulated in Table 1 as shown:

Table 1. Physical parameters of the proposed wheelchair system.

Parameter	Definition	Value	Unit
r_w	Radius of wheel	0.3	M
L	Distance between the wheels	0.5	M
M	Mass of wheelchair	100	Kg
I_v	Wheelchair moment of Inertia	100	Kg
I_w	Wheel moment of Inertia	0.006	Kg -m ²
C	Viscous friction constant	0.05	Kg/s
K	Gain driving factor	5	-

4. Controller Design Strategies

In this section we will discuss about the motion control of the smart wheelchair systems using various traditional and intelligent controller design strategies such as PID, Fuzzy Logic, and PSO-Optimized PID controller as discussed below:

4.1. PID Controller

The Proportional-Integral-Derivative (PID) control strategy is most common and highly utilized control technique that is used in almost every discipline of science and engineering. PID controllers are mostly feedback mechanisms that incorporate three different sections: proportional, integral and derivative [28]. Each section of the controller work independently on the error signal and give the result as the sum of all component responses. Figure 3 describes the block diagram of PID control strategy with the proposed mobility system. There are various methods to tune the PID controller including the hit and trial method, Ziegler-Nichols method and Cohen-Coon method. Each method of tuning has its own advantages and drawbacks depends upon the complexity of the system and computational time to fine tune the parameters of the PID controller [46]. In context of PID tuning we used manual tuning method which has a drawback that it is time consuming and hectic. To avoid this limitation, we proposed to tune the PID controller by using Particle Swarm Optimization (PSO). The activation signal of the PID controller is based on the following integro-differential equation as given below:

$$C_a(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{de(t)}{dt} \quad (17)$$

Where K_p , K_d and K_i are the proportional, derivative and integral gain coefficients respectively. Designing a PID control strategy for motion control of wheelchair system involves four important steps: Define the control objective, determine the system model, select an appropriate control strategy and determine the optimal values of PID controller to maintain the desired velocity.

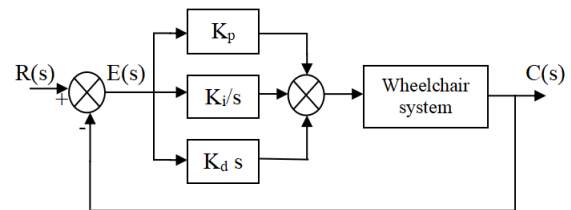


Figure 3. Block diagram of PID Controller with Wheelchair system.

4.2. Fuzzy Logic Controller (FLC)

Fuzzy Logic Controller (FLC) is an advanced intelligent controller that can handle certain system uncertainties and non-linearities in the system. The main advantage of this control strategy is that it don't require any mathematical model unlike in other controllers. Fuzzy Logic Controller (FLC) is a control technique that utilizes fuzzy set theory to build a rule base in control system theory, capable of adapting to different inputs [11, 12, 38, 39]. The FLC design for the motion control of a smart mobility system can be achieved using the following steps:

- 1) Choose appropriate Inputs and Outputs: Here error 'e' and sum of error 'se' are the inputs and output is the 'Speed control' of the FLC control strategy.
- 2) Choose appropriate Fuzzy sets and Membership functions: Appropriate Fuzzy sets and Membership functions

are chosen to change the the different inputs and outputs into equivalent Fuzzy linguistic variables.

3) Formulate the Fuzzy rules: Different rules are formulated based on the different input variables using ‘IF-THEN’ statements connected through Fuzzy logical operations.

4) Define the Fuzzy Inference: It is the process of getting appropriate Fuzzy output with the help of different rules and the input variables. Here Mamdani inference method is used to determine the output as a weighted average of membership values of different fuzzy sets.

5) Perform defuzzification: Defuzzification refers to the process of changing the fuzzy inputs into a single, crisp number. This can be accomplished by computing the weighted average of the output fuzzy sets.

6) Implement the FLC: The FLC can be implemented in software or hardware, depending on the application. The FLC continuously measures the input variables, applies the fuzzy rules, and determines the steering angle of the wheelchair.

A Fuzzy Logic controller is constructed using various linguistic variables in the FIS editor. Suitable membership functions are assigned to these variables, and a rule base is formulated. The fuzzy logic controller designed, work in accordance with the rules made in MATLAB interface. Here three variables are made, two for input and one for output. The two inputs are Error and Sum_Error and output is Desired_Speed. The membership functions for first input are Error_Negative (ERN), Error_Zero (ERZ), and Error_Positive (ERP). The membership functions for second input are Sum_Error_Negative (SEN), Sum_Error_Zero (SEZ) and Sum_Error_Positive (SEP). Similarly membership functions for Output can be

Negative (N_o), Positive (P_o) and Zero (Z_o). The different rules framed are shown in Table 2. Figure 4 depicts the MATLAB interface for different variables. Figure 5 highlights the Fuzzy logic Interface for different rules in three dimensional view using Fuzzy logic Toolbox.

Table 2. Fuzzy Rule table.

Error/Sum_error	SEN	SEZ	SEP
ERN	N_o	N_o	Z_o
ERZ	N_o	Z_o	P_o
ERP	Z_o	P_o	P_o

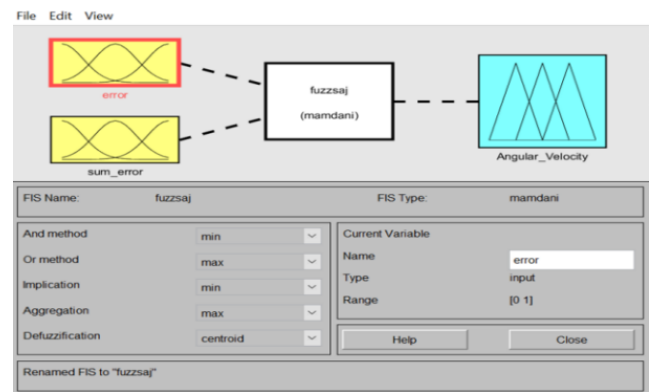


Figure 4. MATLAB interface for different variables.

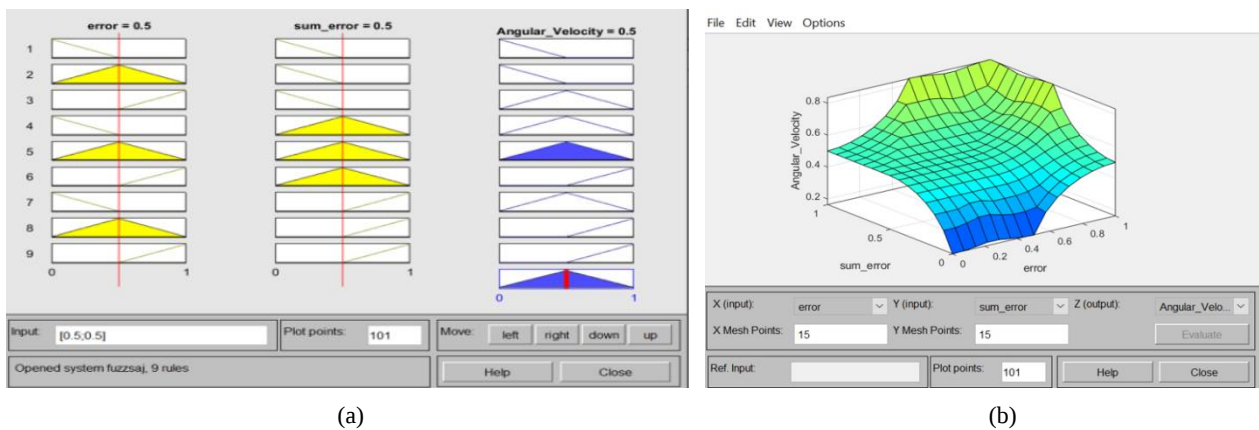


Figure 5. Fuzzy Logic interface in MATLAB using “Fuzzy-Logic-Designer” (a) Interface for rules (b) Three dimensional view of different Inputs and output.

4.3. PSO-Optimized PID Controller

Particle Swarm Optimization (PSO) is a metaheuristic optimization technique drawing inspiration from the social behaviors observed in bird flocks and fish schools. Originally proposed as a method for optimizing nonlinear functions, PSO

has since gained widespread popularity as an optimization technique across various domains, including engineering, economics, and finance. The algorithm operates on the principle of particles traversing a search space and interacting with one another to locate the best or optimal solution. Each particle in the swarm represents a possible solution to the optimization problem and continuously search for the best optimal position

in the search domain. The PSO algorithm commences by randomly selecting a set of particles within the search domain.

$$V_i(t+1) = w_i V_i(t) + c_a r_a (P_{best} - X_i(t)) + c_b r_b (G_{best} - X_i(t)) \quad (18)$$

$$X_i(t+1) = X_i(t) + V_i(t+1) \quad (19)$$

Where $V_i(t+1)$ is the updated value of velocity for particle i at time $t+1$, $X_i(t+1)$ is the updated value of position for particle i at time $t+1$, G_{best} is the best position found by any particle, P_{best} is the best position found by any particle i so far in the swarm, w_i is the inertia weight constant, r_a and r_b are random numbers with values between 0 and 1 and c_a and c_b are the acceleration constants. If the new position value of an agent in the swarm improves over its previous best position value (P_{best}), the particle updates its P_{best} value to the new updated position value. Similarly, if the new position value surpasses the current global best position value (G_{best}), the G_{best} is updated to the new position value. The PSO technique continues to iterate until a stopping condition is reached. This process of optimization is best illustrated by a flowchart as shown in Figure 7.

PSO offers several advantages over other optimization

Each particle in the swarm is assigned an initial value for Position and Velocity and these values are iteratively updated by the following given expressions: [31].

techniques. One notable advantage is its ease of implementation, requiring minimal parameter tuning. PSO is also able to handle optimization problems with non-convex, multimodal, or noisy objective functions. As technology continues to advance, it is likely that PSO will become even more important in the field of control and robotics. Particle Swarm Optimization (PSO) serves as a population-based optimization algorithm suitable for optimizing the parameters of a PID controller in motion control applications, such as those found in smart wheelchair systems. The PSO-optimized PID controller design for velocity control of a smart autonomous wheelchair system is shown in Figure 6, where V_{rd} , V_{rl} , V_{ra} , V_{la} , e_r and e_l denote the desired speed of right wheel, desired speed of left wheel, actual speed of right wheel, actual speed of left wheel, speed error of right wheel and speed error of left wheel respectively. PSO-optimized PID control strategy can be achieved using the following steps: [29, 30, 33, 34, 36, 45].

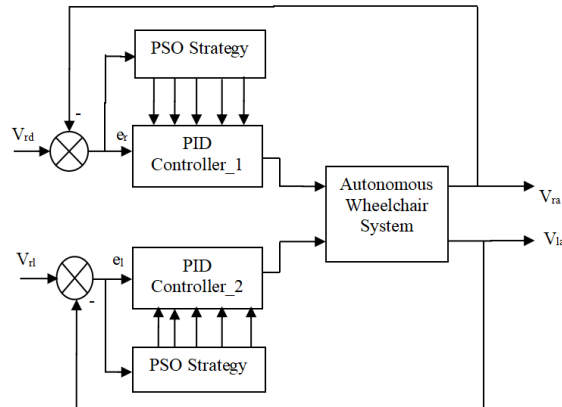


Figure 6. Block diagram of the proposed PSO-Optimized PID Controller.

- 1) Define the control objective: The control objective is to maintain a constant speed while navigating through different terrains, avoiding obstacles and adapting to user preferences.
- 2) Determine the system model: The system model describes the connection between different control inputs and the output response. In this case, the system model could be a transfer function that relates the speed and heading angle of the mobility system to the system input, which is the motor voltage.
- 3) PID controller design: The PID control strategy is initially started by obtaining the controller gains determined through manually or using any alternative tuning methods. The control signal is computed as the sum of

the three terms (proportional, integral and derivative) of the error between the desired and actual values of speed of the mobility system.

- 4) Define the Fitness function: Fitness function is a measure of the performance of the PID control strategy, which is utilized to obtain the fitness of each individual particle in the group. The Fitness function can be defined as the Root Mean Square (RMS) value of the error or Integral of square error (ISE) between the desired and actual speed of the mobility system over a given set of simulation trails.
- 5) Initialize the PSO algorithm: The PSO algorithm starts with the initialization of particles in the swarm, where

each particle represents to a set of PID gains. These particles are randomly initialized within a search domain depicted by the maximum and minimum values of each gain.

- 6) Update the position of particles: The particle values are updated for each iteration based on their current values of position and velocity in the swarm.
- 7) Evaluate the fitness of each agent: The fitness of each agent is assessed utilizing the fitness function. The particles exhibiting the best fitness are preserved as the global best and local best positions.
- 8) Update the velocity and position values of agents: These two individual metrics undergo changes based on the global and local best positions. This updating process persists until a convergence criterion is satisfied.
- 9) Implement the PSO-optimized PID controller: The optimized PID gains are used to implement the PSO-optimized PID controller for motion control of the smart mobility system.

The ultimate position of the best particle denotes the optimized PID controller parameters for the speed control of the given system. Figure 7 shows the flowchart of the PSO algorithm that is used in the proposed strategy. MATLAB code for implementing the PSO algorithm to optimize the PID controller's parameters for wheelchair velocity control is executed at various swarm sizes and numbers of iterations to obtain the optimal values. The operation of the proposed control strategy is executed through the following steps:

Step 1. The parameters of the technique, such as the maximum number of iterations ($iter_{max}$), number of generations, swarm size, inertia weight constants w_{min} and w_{max} are initialized.

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. Fitness value of each agent in the swarm 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 (P_{best}) and global-best (G_{best}) values of individuals in the swarm are evaluated based on Fitness function evaluated in step 4.

Step 6. The values Velocity and Position values of agents are updated based on expressions as given in equations (18) and (19) respectively.

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

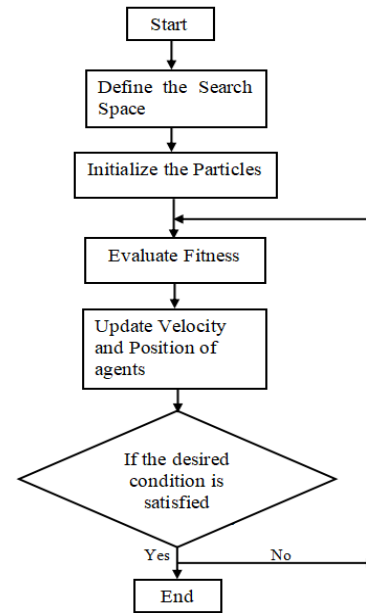


Figure 7. Flowchart of the PSO Algorithm.

5. Results and Discussions

This research paper presents a simple and comprehensive approach for designing the kinematic model and motion control of a mobility system. Different classical and intelligent controller design strategies are used like PID, Fuzzy and PSO optimized PID to provide a means of achieving precise and smooth motion control of the mobility system. To compare the performance of these control strategies, we conducted experiments on a differential drive type model of the system in a simulated environment using MATLAB/Simulink. 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 gave 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 below, 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.

The simulation results of the different controllers and strategies can be evaluated by using various forms like tables, charts and graphs. These results can be utilized to describe the working and efficiency of the different controllers and optimization techniques. Here a step response graph is utilized to show the performance of different controllers. The step response characteristics explain how the actual response responds for a step input. Figure 8 depicts the open-loop, closed-loop, PID and Fuzzy logic controller responses. Figure 9 shows the relative performance of different controllers. Figure

10 describes the step responses of the speed of wheelchair using PSO-optimized PID controller. Figure 10(a) shows the response for swarm size 20, maximum iteration 50, $w_i=0.8$ and $c_a=c_b=1.4$, 10(b) shows the response for swarm size 30, maximum iteration 80, $w_i=0.8$ and $c_a=c_b=1.5$, 10(c) shows the response for swarm size 40, maximum iteration 80, $w=0.9$ and

$c_a=c_b=1.6$, 10(d) shows the response for swarm size 50, maximum iteration 100, $w_i=0.8$ and $c_a=c_b=2$. From all these responses, it is clear that the PSO-Optimized PID controller shows better results in terms of steady-state error, rise-time, delay-time and peak-overshoot as compared to other controllers which is highlighted in Table 3.

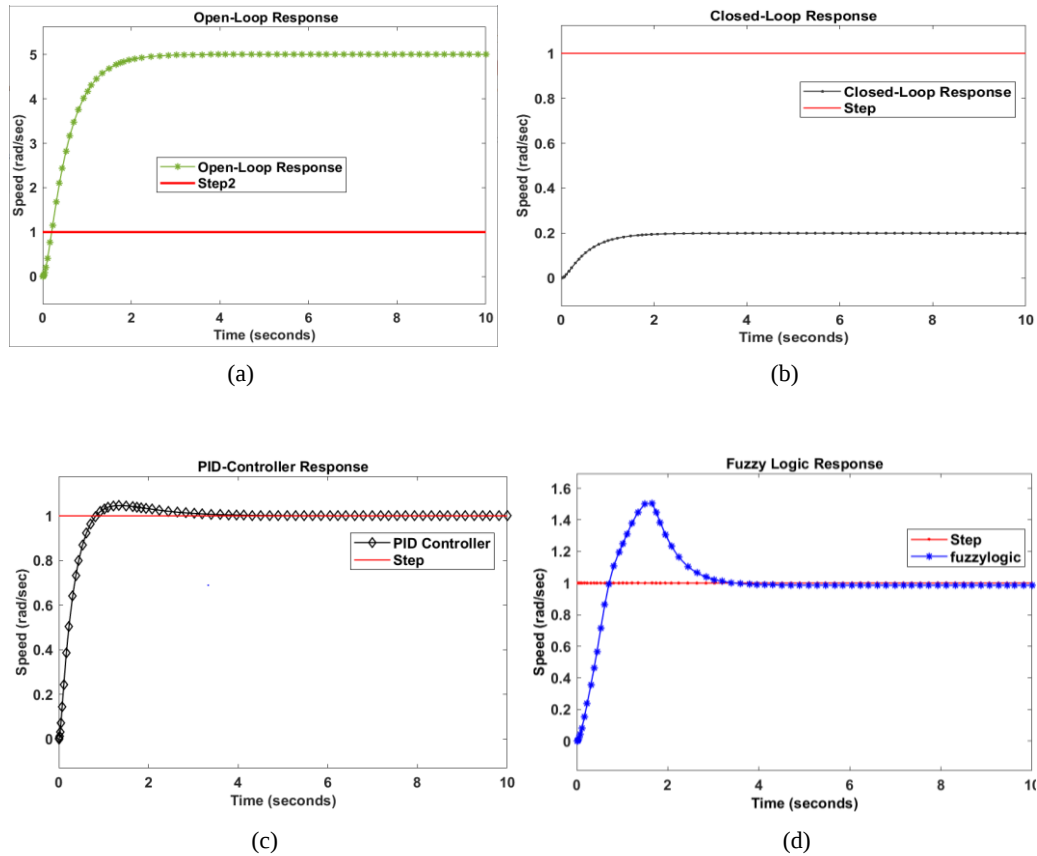
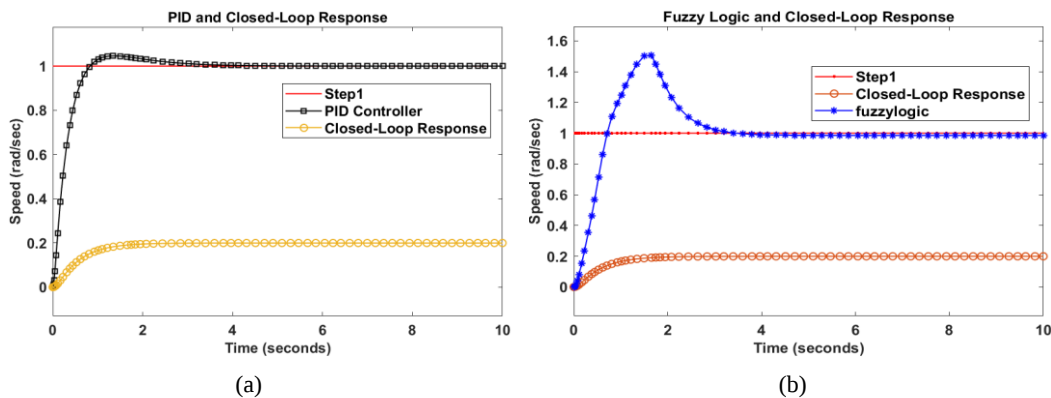


Figure 8. Step response of different configurations: (a) Open-loop response; (b) Closed-loop response; (c) PID controller response; (d) Fuzzy logic response.



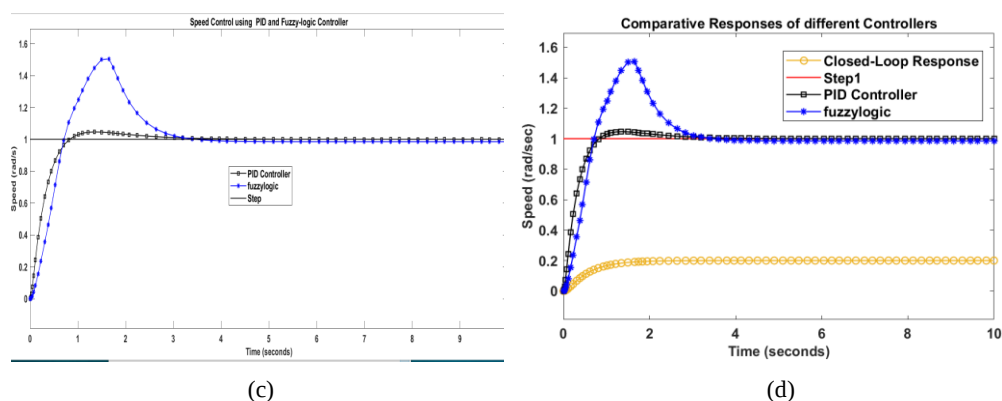


Figure 9. Comparative step responses of different configurations: (a) PID and Closed-loop response; (b) Fuzzy-logic and Closed-loop response; (c) PID and Fuzzy-logic response (d) PID, Fuzzy-logic and Closed-loop response.

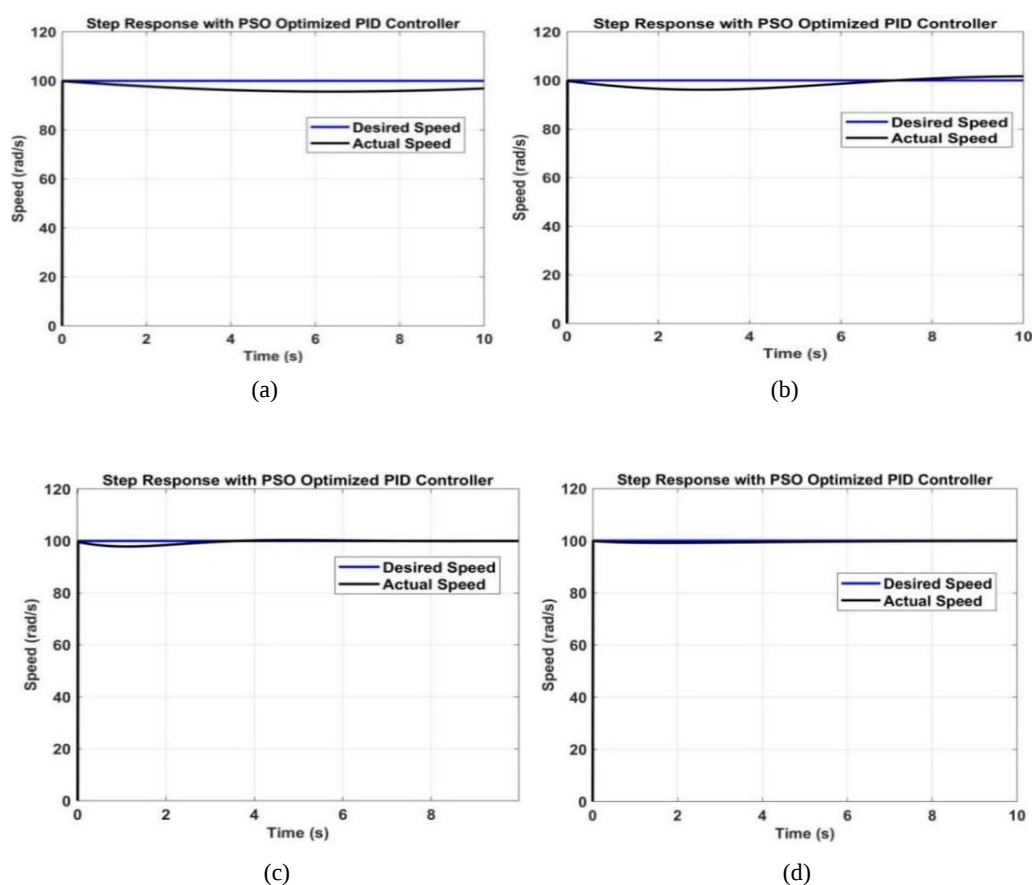


Figure 10. Step response by using PSO optimized PID controller (a) For swarm size 20 and maximum iteration 50 (b) For swarm size 30 and maximum iteration (c) For swarm size 40 and maximum iteration 80 (d) For swarm size 50 and maximum iteration 100.

Table 3. Comparative Analysis of different Controllers.

Controller Type	Settling-Time (s)	Rise-Time (s)	Peak-Overshoot (%)	Steady-state error (%)
Open-loop	3	0.4	0	400
Closed-loop	2	-	0	80
PID	3.8	0.9	8	0
Fuzzy	3.6	0.8	58	0

Controller Type	Settling-Time (s)	Rise-Time (s)	Peak-Overshoot (%)	Steady-state error (%)
PSO-PID	0.1	0.05	0	0

6. Limitations of Existing Work and Future Research Work

The present study is limited to MATLAB-based simulation results, which may not capture real-world uncertainties such as sensor noise, actuator nonlinearities, and external disturbances. Human interaction, safety constraints and user comfort have not yet been experimentally validated. Future work could involve Artificial Neural network (ANN), Grey wolf optimization (GWO) and GA-Optimized PID control strategies. Furthermore future research directions could include the following:

- 1) Hardware-in-the-Loop (HIL) testing to validate controller performance under real-time constraints.
- 2) Real-world prototype development using BLDC motor drives and embedded controllers.
- 3) Human-in-the-loop experimental validation to assess usability, comfort, safety and adaptability for individuals with disabilities.

7. Conclusions

The proposed approach involves the design and implementation of a smart wheelchair with a differential drive system. The kinematics equations are derived and the speed control system is designed using a PID, Fuzzy and a PSO optimized PID control strategy. The performance of these control strategies is evaluated and compared through simulations in terms of tracking accuracy, settling time, peak overshoot and rise time to determine the most effective control strategy. The results showed that the PSO optimized PID controller has the highest accuracy and stability, while the fuzzy logic controller has the advantage of being more adaptable to changing conditions. Ongoing research is needed to further refine these approaches and address the unique challenges of this domain. The research work has some limitations, including the simplifying assumptions made in the kinematical model and the lack of real-time experiments. Overall, the PSO optimized PID controller for the motion control of a smart mobility system is a promising research area that can lead to improved performance and efficiency in various industrial and robotic applications.

Abbreviations

PID Proportional Integral Derivative

FLC	Fuzzy Logic Controller
BLDC	Brushless DC Motor
PSO	Particle Swarm Optimization
ANN	Artificial Neural Network
GA	Genetic Algorithm
ACO	Ant Colony Optimization
GWO	Grey Wolf Optimization
FIS	Fuzzy Inference System
ISE	Integral Square Error

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Conflicts of Interest

The authors declare that they have no known financial, commercial or personal relationships that could be perceived as potential conflicts of interest in the conduct and preparation of this manuscript. The research was carried out independently and all findings, interpretations and conclusions presented are solely those of authors.

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