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Motion Control of Autonomous Mobility System Using Fuzzy-PID Controller

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***Abstract*:** Autonomous mobility systems play a pivotal role in enhancing the quality of life and independence of users who are suffering from mobility restrictions. This research work presents a novel approach in the design and implementation of a Fuzzy-PID control strategy for the velocity control of a differential drive type wheelchair system. Smart autonomous wheelchairs offer maneuverability and versatility but precise motion control of these systems is crucial for overall user comfort, safety and safe path planning. The proposed strategy combines the adaptability of Fuzzy logic with the precision of PID control strategy to enhance the performance of the system in dynamic operating conditions. The design process involves kinematic modeling of the system, development of hybrid Fuzzy-PID control strategy and tuning of PID controller using MATLAB/Simulink toolbox. Through comprehensive design of the system and testing by using different simulations, this control strategy offers superior tracking accuracy, minimal response time and improved stability and robustness. Overall the combination of fuzzy logic with conventional PID control strategy offers promising results as compared to standalone PID and Fuzzy control strategies in the field of Rehabilitation engineering and Assistive technology.

***Keywords*:** Autonomous Wheelchair, Differential drive, Design kinematics, Fuzzy-PID controller, Motion control, Assistive technology

1) Introduction

Independent mobility is very important and crucial factor for every organism in this universe especially for human beings. The rapid advancement of autonomous mobility systems has significantly influenced various domains, particularly in enhancing the mobility and independence of individuals with disabilities [1]. Smart wheelchairs, as a subset of autonomous mobility systems, offer a transformative solution by providing users with increased autonomy and improved quality of life. These advanced wheelchairs are equipped with intelligent control systems that enable them to navigate through complex environments, avoid obstacles and follow specific paths without constant human intervention. The concept of autonomous smart wheelchair system is an innovative idea which assist the patients suffering from different diseases like cerebral palsy, quadriplegia or any other physical disability in moving from one place to another [2],[5]. Differential drive type wheelchairs are the type of mobility aids for people with different types of disabilities which hamper their freedom of movement. The precise and efficient control of these wheelchairs is critical factor to ensure smooth and safe movement through different terrains. The core functionality and performance of smart wheelchairs heavily depend on the effectiveness of their kinematics and speed control systems. Achieving precise motion control is a crucial factor for ensuring the safety, reliability and overall user comfort of these systems. Traditional controller design strategies like PID and LQR have been used to control the speed and trajectory of smart wheelchairs. However these types of strategies often struggle to adapt to dynamic and non-linear uncertainties encountered during the journey. To avoid these challenges, this research work proposes a hybrid Fuzzy-PID control strategy for the motion control of a differential drive type smart mobility system. Integration of PID with Fuzzy logic controller gives a mechanism which handle imprecise and uncertain information present in the wheelchair dynamics and hence ensures the proper smooth motion of wheelchair system.

A lot of research work has been published related to the design and development of smart wheelchair. The literature on smart wheelchair comprises a range of methodologies and strategies aimed at improving the overall motion control and user experience for people suffering from different types of disabilities which hamper their normal motion. Design and implementation of smart wheelchair using multiple controller interfaces is presented based on the conventional wheelchair model which is available in the market. The wheelchair prototype is developed with gesture and voice controlling interfaces in addition to conventional joysticks [1]. Design and development of a Kinect-Wheelchair Interface Controlled (KWIC) smart wheelchair is introduced for patients suffering from different types of disability adapted with shared control. This smart wheelchair uses computer vision to create a virtual tether background between the user and the wheelchair [2]. A coordinated control based strategy has been developed for a four wheel vehicle using PID controller [3]. This strategy aimed to enhance trajectory tracking performance of the vehicle to achieve longitudinal speed tracking. Traditional controllers like PID are widely used in the velocity control of autonomous agents due to their simplicity and flexibility. Proportional-Integral-Derivative (PID) controllers are widely recognized for their simplicity and effectiveness in a broad range of applications. Ameer L. Saleh et al. explored the speed control of an autonomous wheeled mobile robot using a fractional-order PID controller, demonstrating enhanced performance in trajectory tracking [6]. Similarly, PID controllers have been utilized for the path tracking and speed control of various robotic systems, including smart wheelchairs, due to their ability to provide stable and reliable control. Design kinematics and velocity control for a differential drive robot is proposed by Shahida Khatoon et al.[4]. In this study a PID controller is utilized to control the motion of the system using different simulations in MATLAB.

Design kinematics and velocity control of autonomous agents using traditional controllers like PID has been developed for smooth control of these autonomous systems. However, the manual tuning of PID gains can be challenging and may not always yield optimal results, especially in dynamic environments. In this context, researchers and engineers have find alternative control approaches and techniques to address these challenges and difficulties with a particular focus on the design and velocity control of these smart wheelchair systems. Some of these strategies are Fuzzy logic, Artificial neural networks (ANNs), adaptive control and Model predictive control (MPC). Fuzzy logic technique gives a framework for handling uncertain and imprecise data making it quite suitable for applications where accurate mathematical model is unknown. Fuzzy Logic Controllers (FLCs) represent an advanced control technique that utilizes fuzzy set theory to handle uncertainty and imprecision in control systems. By extending different linguistic variables and fuzzy inference systems, fuzzy logic technique often proved better than other techniques in terms of adaptability,robustness and diverse operating conditions. Mauro Callejas-Cuervo et.al designed and implemented fuzzy logic for the position, speed and orientation which involves head movements to operate a wheelchair prototype [5]. In this study, research is divided into four sections including software implementation, hardware implementation, position.speed and orientation control and system verification using both electronic controller and practical user experience.Intelligent controller design using fuzzy logic is developed by SA Wani et. al [13]. Here mathematical modelling is done using the characteristics of brush less gear motor in MATLAB/Simulink. MATLAB simulation using Fuzzy logic controller is done for mobile robot navigation is proposed by Anish Pandey et. al. This control strategy generates suitable steering angle to reach the final destination without any collision with the obstacles [14],[15]. In another study by Fahmi Zal et al., Fuzzy controller based Subsumption Architecture as a sensor fusion technique for autonomous robotic wheelchair system is proposed. Here the system is controlled by a microcontroller for motion control with the help of a web-camera for local visualization [17]. Several studies have investigated the integration of fuzzy logic with PID controller highlighting the improved results in terms of trajectory tracking and obstacle avoidance. Do Khac Tiep et. al designed a Fuzzy-PID controller for path tracking of a mobile robot with differential drive mechanism [18]. Here the proposed controller is compared with classical PID controller and it shows that the proposed strategy gives better results as compared to classical one.

There can be nature inspired techniques like Particle swarm optimization (PSO), Grew wolf optimization (GWO), Ant colony optimization (ACO), Genetic algorithm (GA), Simulated annealing and many more, integrated with PID and Fuzzy logic controllers used for the optimal controller design of different autonomous agents Several studies have used PID controller optimized with PSO and ACO for the velocity control and path planning of different autonomous agents like mobile robots and smart wheelchair systems [29-32],[36]. Andi Adriansyah et. al demonstrated a wall following robot for velocity control using PSO optimized PID controller [29]. Here PSO is used to automatically select the values of different parameters of PID controller. In another work PSO is used to optimize the PID controller to adjust the controller parameters for velocity control in an unknown environment having rough terrain [30]. Motion control of a unicycle type mobile robot is executed using optimal PID controller optimized with PSO optimization technique. The proposed results using this technique is compared with the response got from Genetic algorithm (GA) optimized PID controller and the response without using any controller [35]. Energy comparison of different controllers used in autonomous agents is crucial which is related to tracking accuracy [11]. Here the kinematic and dynamic model of the system is developed to determine the position,speed, angular velocity,trajectory length and total time taken to cover the journey.

This research work comprehensively explores the design kinematics and implementation of the Fuzzy-PID controller, starting from the kinematic considerations of the differential drive wheelchair to the validation of the performance of the controller using MATLAB/Simulink. The primary objective is to enhance the precision and responsiveness of the wheelchair's motion control mechanism while ensuring better user safety and comfort. Each controller was evaluated through extensive simulations conducted in MATLAB/Simulink, focusing on key performance metrics such as rise time, settling time, overshoot, steady-state error and disturbance rejection. Through Simulation results and discussions, the study evaluates the performance of the proposed controller in comparison to classical PID control methods, highlighting its advantages and potential for enhancing wheelchair mobility and overall user experience.

The paper is structured as follows: In section III, Design Kinematics of the differential drive type mobility system is presented. Implementation of different controller design strategies is presented in section III. Section IV presents the simulation environment and the results obtained with the comparative performance of each controller design strategy. Finally section V offers conclusions and talks about the future research work in this field of engineering.

2) Design Kinematics of Differential Drive Wheelchair

The design kinematics of a differential drive type wheelchair system is very important in determining maneuverability, stability and overall efficiency of the system. A fundamental understanding of the relationship between wheel velocities and the motion of the wheelchair is useful in developing effective control methods. This section explains the key aspects required in the design kinematics of a Differential drive type wheelchair system [7],[11].

1) Kinematic Model: The differential drive type wheelchair usually have two independently controlled wheels located on either side of the wheelchair system driven by two motors , allowing a precise control of the rotational velocity of the wheels. The kinematic model of the differential drive system is essential for understanding the motion of the wheelchair influenced by the velocities of two independent driven wheels. This model is responsible for developing the relationship between the linear and angular velocities of the wheelchair system and the rotational velocities of the two wheels. The two dimensional model and the kinematic equations are shown in figure 1. The important parameters of the differential drive type wheelchair as shown in figure are given as below:

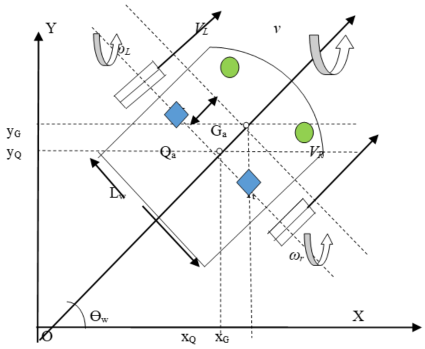


Fig.1 Two dimensional Model of Differential Drive type Wheelchair system

V : Linear velocity of the differential drive type wheelchair system (ms^{-1})
θ_w : Orientation of the system (rad)
ω_L : Left wheel Angular velocity ($rads^{-1}$)
ω_R : Right wheel Angular velocity ($rads^{-1}$)
V_L : Left wheel Linear velocity (ms^{-1})
V_R : Right wheel Linear velocity (ms^{-1})
r_t : Radius of wheels (m)
L_w : Distance between two wheels (m)
Q_a : Center of axis between the two wheels
G_a : Center of axis between the two wheels
k : Distance between Q_a and G_a

The Kinematic equations of the model shown in figure 1 are based on Differential drive system and are given as:

$$x_G = x_Q - kCos\theta_w \quad (1)$$

$$y_G = y_Q - kSin\theta_w \quad (2)$$

We assume that the wheels are rolling without slippage, the center of gravity coincides with the center of axis. Based on the given kinematic model shown in figure 1 we get:

$$V_R = V + \frac{L}{2}\dot{\theta_w} \quad (3)$$

$$V_L = V - \frac{L}{2}\dot{\theta_w} \quad (4)$$

Adding and subtracting equations 3 and 4 we get:

$$V = \frac{V_R + V_L}{2} \quad (5)$$

$$\dot{\theta_w} = \frac{V_R - V_L}{L} \quad (6)$$

Due to non-slippage assumptions we have:

$$V_R = r_t \omega_R \quad (7)$$

$$V_l = r_t \omega_L \quad (8)$$

From the model as shown in figure 1 we get:

$$\dot{x} = \dot{x_Q} = V\cos\theta_w \quad (9)$$

$$\dot{y} = \dot{y_Q} = VSin\theta_w \quad (10)$$

$$\dot{\theta_w} = \omega \quad (11)$$

Equations 9, 10 and 11 are known as the Kinematic model of the differential drive type wheelchair systems

2) Motor Dynamics: DC motor modeling involves understanding its electrical and mechanical characteristics. In electrical domain it is represented by equations in terms of voltage, current and resistance. In mechanical system, it is represented by equations consisting torque, speed and inertia [13],[11]. These equations can be utilized to simulate and control the behaviour of DC motor. The electrical circuit and the free body diagram of the motor rotor of a DC motor are depicted in figure 2 as shown below:

The equation representing the mechanical dynamics of the DC motor is given by :

$$J\frac{d^2\theta_m}{dt^2} + B\frac{d\theta_m}{dt} = K_t I_a \quad (12)$$

$$L_{ar}\frac{d\theta_m}{dt} + R_{ar} I_a = V - K_e\dot{\theta}_m \quad (13)$$

The parameters given in equations 12 and 13 are described below:
J : Moment of Inertia (Kgm^2)
θ_m : Angle of rotation of output shaft (rad)
T : Mechanical Torque developed in the motor (N-m)
V : Applied voltage (V)
I_a : Armature current (A)
K_t : Armature constant
B : Damping coefficient
K_e : Motor constant
R_{ar} : Armature Resistance (Ohm)
L_{ar} : Armature Inductance (H)

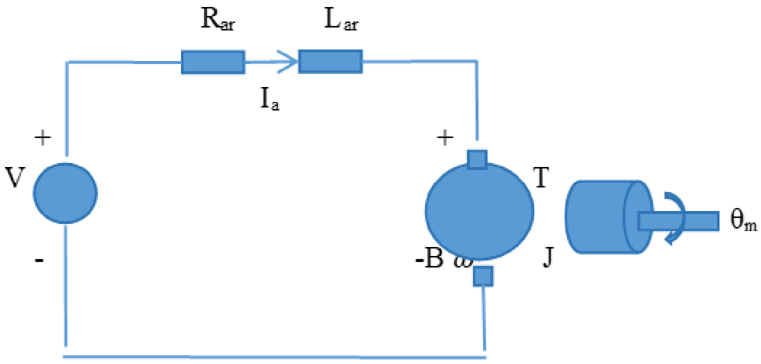


Fig. 2 Basic circuit diagram of DC motor with free body diagram of motor rotor

The Laplace transform of equations 12 and 13 are given by :

$J^2 s^2 \theta_m(s) + Bs\, \theta_m(s) = K_t I_a(s)$ (14)

$L_a s I_a(s) + R_a I_a(s) = V(s) - K_e s\, \theta_m(s)$ (15)

From equations 14 and 15 we get:

$J^2 s^2 \theta_m(s) + Bs\, \theta_m(s) = K_t \frac{V(s) - K_e S \theta_m(s)}{R_a + sL_a}$ (16)

The Transfer function of the Angular velocity ω(s) to the Input voltage V(s) is given by :

$F(s) = \frac{\omega(s}{V(s)} = \frac{K_t}{(R_a + sL_a)(Js+B) + K_t K_e}$ (17)

Or $F(s) = \frac{b}{s^2 + a_1 s + a_0}$ (18)

Or $F(s) = \frac{\frac{K_t}{JL_a}}{s^2 + \frac{R_a J + L_a}{JL_a} + \frac{R_a B + K_{t+K_e}}{JL_a}}$

Where

$b = \frac{K_t}{JL_a}$; $a_1 = \frac{R_a J + L_a}{JL_a}$; $a_0 = \frac{R_a B + K_{t+K_e}}{JL_a}$

3) Implementation of different Controller Design Strategies

This section highlights the implementation of Proportional-Integral-Derivative (PID), Fuzzy and hybrid Fuzzy-PID controllers for the motion control of a smart mobility system. The objective is to compare the performance of these control design strategies in terms of response-time, tracking accuracy, overshoot and stability under various operating conditions. Each controller was designed, simulated and tested to ensure reliable performance of the strategy.

A. PID Controller

The Proportional-Integral-Derivative (PID) controller is a traditional control strategy mostly used in control system applications for its simplicity and effectiveness. In context to the motion control of the smart wheelchair system, the PID controller continuously calculates the error $e_w(t)$ between the desired and the actual values of the output quantity. The controller tries to minimize the error by adjusting the control signal $u_w(t)$ of the system [4],[6],[22]. The PID control law is represented by the following expression:

$u_w(t) = K_p.\, e_w(t) + K_i.\int e_w(t)dt + K_d.\frac{de_w(t)}{dt}$ (19)

- Proportional Term: The proportional term $K_p e_w(t)$ gives the output that is directly proportional to the current error signal. A higher K_p value is followed by the higher change in control input for a given error signal hence providing a faster response. However too much higher value of K_p makes the system unstable.
- Integral Term: The integral term $K_i \int e_w(t)dt$ combines the past errors over time and hence provide a cumulative correction to the system. This term is responsible for reducing the steady-state error and hence ensuring the system response reaches the set point without any dc offset. However larger value of K_i may cause unwanted overshoots and instability to the system.
- Derivative Term: The derivative term $K_d \frac{de_w(t)}{dt}$ estimates the future error based on the rate change in the error signal. This term provides a damping effect, reducing the peak-overshoot and hence try to improve

the stability of the system. However derivative term is sensitive to noise in the error signal which can cause error in the control input signal.

Tuning of PID controllers is crucial in attaining the desired values of the control parameters (K_p ,K_i , and K_d). The Ziegler-Nichols method is used in in determining the values of the control parameters. In this method, the value of K_i and K_d is initially put to zero and K_p is increased until the system output oscillates at a constant amplitude. The critical gain K_c and period of oscillation T_c are then used to calculate the PID parameters as follows:

$K_p = 0.6\ K_c$, $K_i = 2\,\frac{K_p}{T_c}$, $K_d = \frac{K_p T_c}{8}$

The PID controller was implemented in MATLAB/Simulink where the smart wheelchair system was modeled using the DC motor. The control algorithm was integrated into the model, allowing for real time simulation and testing. The performance was evaluated based on standard metrics such as rise-time, settling time, overshoot and steady-state error. In the simulation work, the PID controller effectively regulated the velocity of smart wheelchair system, getting a quick response with minimal overshoot and steady-state error under normal circumstances.

B. Fuzzy Logic Controller

Fuzzy logic controller (FLC) is an advanced soft computing technique that deals with the inherent uncertainties and non-linearties in the system. The main advantage of using Fuzzy logic controller (FLC) is that it doesn't require a precise mathematical models unlike in case of traditional controllers like PID and LQR controllers. FLCs utilize linguistic variables and fuzzy logic to mimic the human nature of reasoning and decision making processes. In context of smart mobility system, the FLC is designed to give robust and adaptive velocity response.There are four components in fuzzy logic controller: Fuzzification, Rule base, Inference engine and Defuzzification. Each component plays a crucial role in obtaining the appropriate control action from a lot of input signals [13-19].

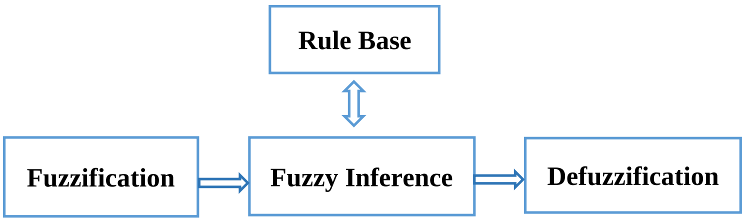


Fig. 3 Block diagram of Fuzzy Logic controller

The FLC for the smart wheelchair system was designed using MATLAB/Simulink's Fuzzy Logic Toolbox. Membership functions for the input variables 'e_w' and 'Δe_w' were created. Here five linguistic terms are made which are Negative Large (NE_L), Negative Small (NE_S), Zero (ZE), Positive Small (PO_S) and Positive Large (PO_L). A dedicated rule base was formulated to cover various operational scenarios. The Mamdani Inference scheme was selected for its simplicity and effectiveness in control applications. AND operation is used for minimum operator and OR operator is used in place of maximum operation. The Centroid method was selected for the defuzzification because of its advantage to provide a smooth control signal. The FLC was integrated into the smart wheelchair model in MATLAB/Simulink. The controller's performance was tuned by adjusting the membership functions and rule base to achieve optimal control characteristics. Here step input is used to test the performance of FLC. The simulation results showed that the FLC provided smooth and stable velocity control, effectively taking care of various uncertainties and nonlinearties present in the system. Compared to PID controller, FLC exhibited superior performance in terms of stability and robustness, though it had a slightly undesirable response time which was rectified by using hybrid Fuzzy-PID controller. Table 1 illustrates the rule base for the Fuzzy Logic controller. This table maps the Fuzzy inputs (e_w and Δe_w) to the Fuzzy control output (u_w). Following points illustrate the rules of the below table:

Table 1. Rule Base table for FLC

$e_w/\Delta e_w$	NE_L	NE_S	ZE	PO_S	PO_L
NE_L	NE_L	NE_L	NE_L	NE_S	ZE
NE_S	NE_L	NE_S	NE_S	ZE	PO_S
ZE	NE_S	NE_S	ZE	PO_S	PO_S
PO_S	NE_S	ZE	PO_S	PO_S	PO_L
PO_L	ZE	PO_S	PO_L	PO_L	PO_L

- When the error and change in error are large and negative (NE_L), the control action should be strongly negative (NE_L) to correct the large deviation quickly.
- If the error is large and negative (NE_L) but the change in error is zero or positive, then the control action is less aggressive (NE_S or ZE) since the system is approaching stability.
- When the error is small and negative (NE_S) the control action varies from NE_L to PO_S depending on the change in error. This provides a balanced correction without overcompensating.

C. Fuzzy-PID Controller

The Fuzzy-PID control strategy integrates the conventional PID controller with Fuzzy Logic to enhance the overall performance of the control system. This hybrid control strategy leverages the strengths of both methods. This is the simplicity and effectiveness of PID control and the adaptability and robustness of fuzzy logic controller [10]. In the context of velocity control of the smart wheelchair system, the Fuzzy-PID controller aims to provide better handling of uncertainties and nonlinearties which are present in the system.The Fuzzy-PID controller integrates a Fuzzy logic system into the PID control strategy to dynamically adjust the PID gains (K_p ,K_i , and K_d) based on the current state of the system. The proposed system is depicted by block diagram as shown in figure 4. Similar to the standalone fuzzy logic controller, the inputs to the Fuzzy-PID controller are the error 'e_w' and the change in error 'Δe_w'. These inputs are converted into fuzzy sets using predefined membership functions. Commonly used linguistic terms are Negative Large (NE_L), Negative Small (NE_S), Zero (ZE), Positive Small (PO_S) and Positive Large (PO_L). The rule base for the Fuzzy-PID controller contains IF-THEN rules that determine how to adjust the PID gains in response to the fuzzy input variables. For illustration, "If 'e_w' is Positive Large (PO_L) AND 'Δe_w' is Positive Small (PO_S) THEN K_p is Decrease AND K_i is No change AND K_d is Increase".The rule base is designed to ensure that the PID gains are adjusted dynamically to maintain optimal control performance under varying operating conditions. Figure 7 and 8 depicts the MATLAB interface and the surface view of the fuzzy rule base for the proposed controller. The complete rule base table for the Fuzzy-PID control strategy is given in table 2. The linguistic variables for inputs, error (e_w) and change in error (Δe_w) are NE_L,NE_S,ZE,PO_S and PO_L. The corresponding output adjustments of PID gains (K_p ,K_i , and K_d) can be Decrease Large (DE_L), Decrease Small (DE_S), No Change (NO_C), Increase Small (IN_S) and Increase Large (IN_L). The Fuzzy Logic interface for different variables is shown in figure 5 and the membership functions of different linguistic terms is shown in figure 6. The explanation of the above rule table is summarized by some points as given below:[13],[14].

Table 2. Rule Base table for Fuzzy-PID controller

$e_w/\Delta e_w$	NE_L	NE_S	ZE	PO_S	PO_L
NE_L	K_p:IN_L	K_p:IN_L	K_p:IN_S	K_p:DE_S	K_p:DE_L
	K_i:DE_S	K_i:DE_S	K_i:NO_C	K_i:IN_S	K_i:IN_L
	K_d:DE_L	K_d:DE_L	K_d:DE_S	K_d:IN_S	K_d:IN_L
NE_S	K_p:IN_L	K_p:IN_S	K_p:IN_S	K_p:NO_C	K_p:DE_S
	K_i:DE_S	K_i:DE_S	K_i:NO_C	K_i:IN_S	K_i:IN_S
	K_d:DE_L	K_d:DE_S	K_d:NO_C	K_d:IN_S	K_d:IN_S
ZE	K_p:IN_S	K_p:IN_S	K_p:NO_C	K_p:IN_S	K_p:IN_S
	K_i:NO_C	K_i:NO_C	K_i:NO_C	K_i:NO_C	K_i:NO_C
	K_d:DE_S	K_d:DE_S	K_d:NO_C	K_d:IN_S	K_d:IN_S

PO_S	K_p:DE_S	K_p:NO_C	K_p:IN_S	K_p:IN_S	K_p:IN_L
	K_i:IN_S	K_i:IN_S	K_i:NO_C	K_i:DE_S	K_i:DE_S
	K_d:IN_S	K_d:IN_S	K_d:NO_C	K_d:DE_S	K_d:DE_L
PO_L	K_p:DE_L	K_p:DE_S	K_p:IN_S	K_p:IN_L	K_p:IN_L
	K_i:IN_L	K_i:IN_S	K_i:NO_C	K_i:DE_S	K_i:DE_S
	K_d:IN_L	K_d:IN_S	K_d:DE_S	K_d:DE_L	K_d:DE_L

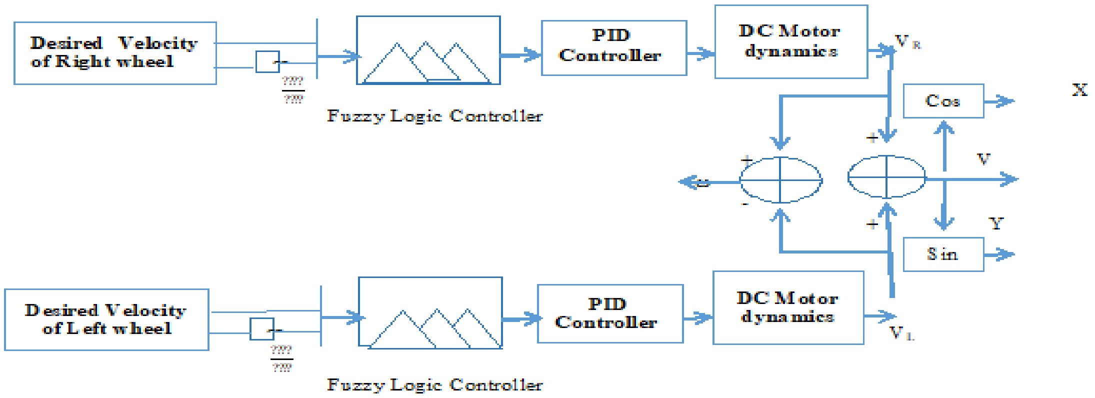


Fig.4 Block diagram of proposed Fuzzy-PID strategy

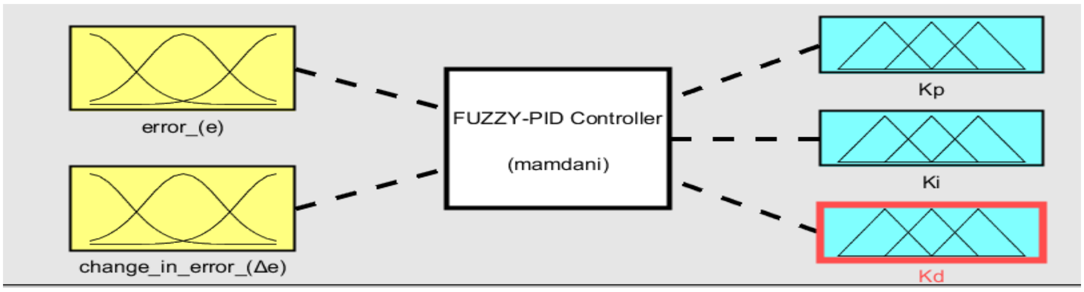
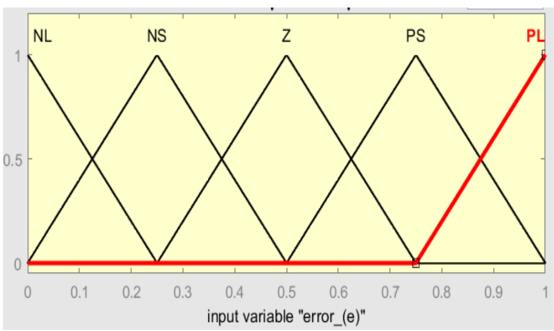
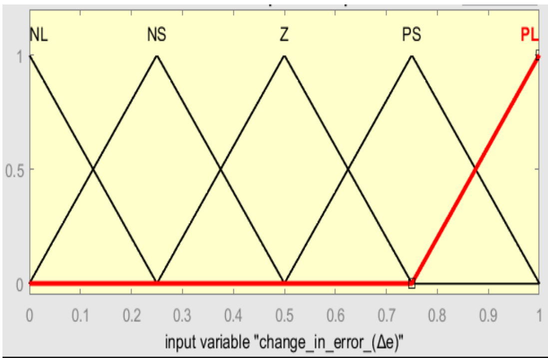


Fig. 5 Structure of Fuzzy Logic controller with inputs and output

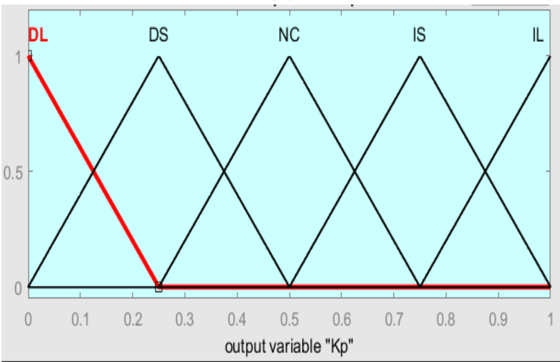
- When the error is Large and Negative (NE_L), the controller should react aggressively to reduce the error. Thus K_p and K_d are increased significantly (IN_L) to provide a strong corrective action while K_i may be decreased (DE_S) to avoid integral windup.
- When the error is Large and Positive (PO_L) , a similar aggressive correction is applied bit in the opposite direction.
- For Small Negative (NE_S) to Positive Small (PO_S) errors, the adjustments are more moderate. K_p is typically increased (IN_S) while K_i and K_d adjustments are more conservative to maintain stability and avoid overreaction.



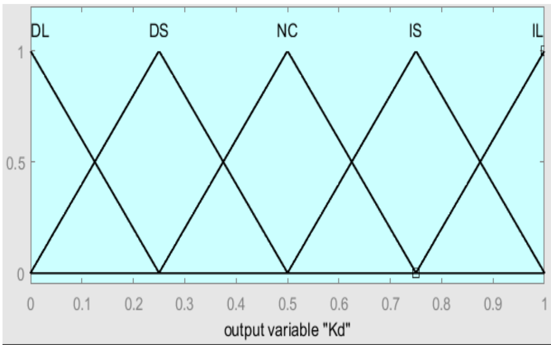
(a)



(b)



(c)



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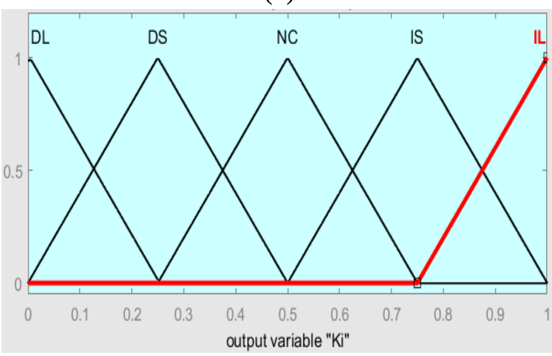

(e)

Fig. 6 Different Membership functions for input and output. (a) error 'e' (b) change in error 'ce' (c) 'K_p' (d) 'K_d' (e) 'K_i'

The Fuzzy-PID control strategy was evaluated through a series of simulations using step input. The results demonstrated that the Fuzzy-PID control strategy significantly improved the system robustness and adaptability compared to standalone PID and Fuzzy Logic controllers. Key performance metrics such as rise-time, settling-time,steady-state error and peak-overshoot were optimized and the system exhibited excellent stability even in the presence of external disturbances and non-linearities.

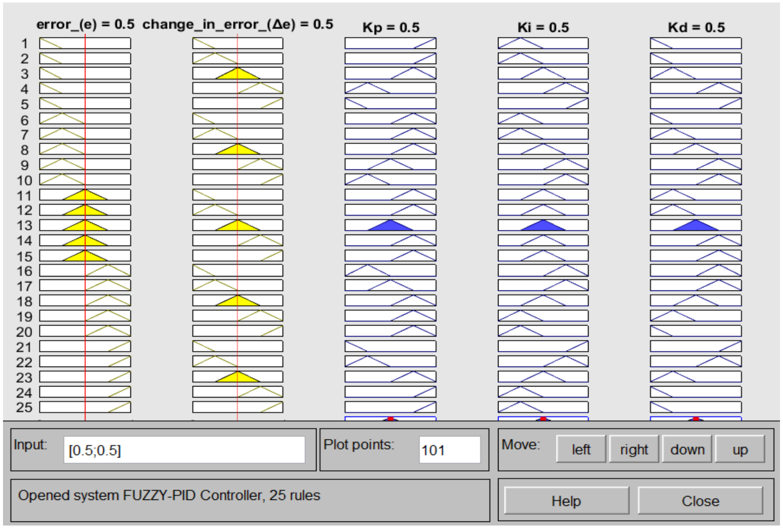

Fig.7 Fuzzy Rule base for the Membership functions

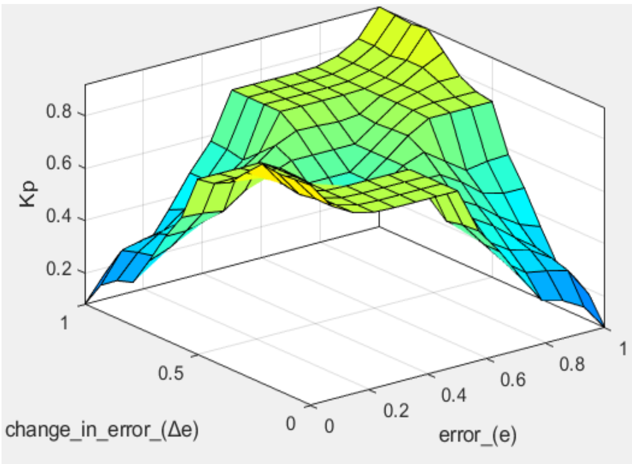

Fig.8 Surface view of Rule base for input and output

3) Results and Discussions

To calculate the working performance of the different controllers used, a number of simulations were conducted in MATLAB/Simulink. The objective of these simulations was to test the controller's performance using step input response.The dynamics of the smart mobility system was modelled and integrated with controllers to observe the effectiveness in maintaining the desired motion under various operating conditions. The performance of these control strategies was assessed based on the following key specifications:

- Rise-time (t_r): It is the time taken response to reach from 10% to 90% of the final desired response.
- Settling-time (t_s): It is the time taken for the response to settle within 5% of the final desired response.
- Peak-overshoot (OS): It is the maximum deviation of the response from its desired value and is calculated as percentage of the final desired value.
- Steady-state error (SSE): It is the error between the desired and the actual value of the response at steady state.
- Robustness: It is the ability of the controller to maintain its original performance in presence of external disturbances.

The PID controller exhibited a fast rise time and acceptable settling time. However it had a significant overshoot, indicating a tendency to overreact to changes in response.The steady-state error was zero, demonstrating good tracking accuracy at maintaining the desired velocity. The Fuzzy logic controller showed a fast rise-time compared to the PID controller but with much overshoot. The settling time was slightly longer, indicating a smoother approach to the desired response. The steady-state error was zero, showing excellent tracking accuracy. The Fuzzy-PID controller achieved a balance between the PID and Fuzzy logic control strategies. It had a fast rise-time and reduced peak-overshoot compared to the PID controller as shown in figures 9 and 10 respectively. The settling-time was the lesser among the three, indicating a quick stabilization at the desired velocity and the steady-state error was also zero. Overall the performance of the Fuzzy-PID control strategy was the best for the motion control of the smart mobility system, combining the advantages of both PID and Fuzzy logic control strategies. The Position, Force and Torque response curves for the right and left wheel of the wheelchair system are shown below in figures from 11 to 16. Table 3 summarizes the performance metrics of the PID, Fuzzy logic and Fuzzy-PID controllers based on the simulation results.

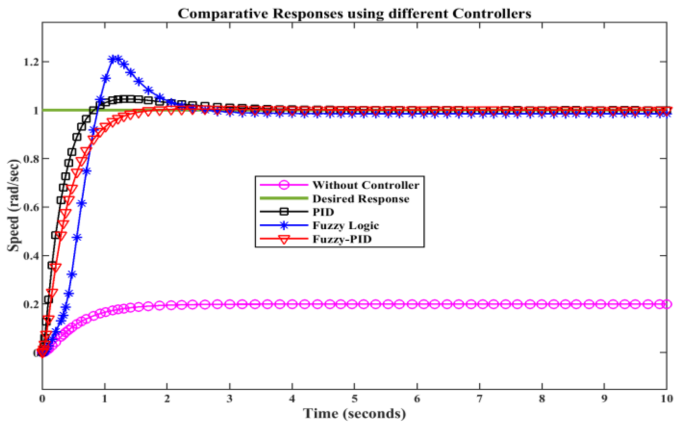

Fig.9 Right wheel velocity of wheelchair using Fuzzy-PID controller

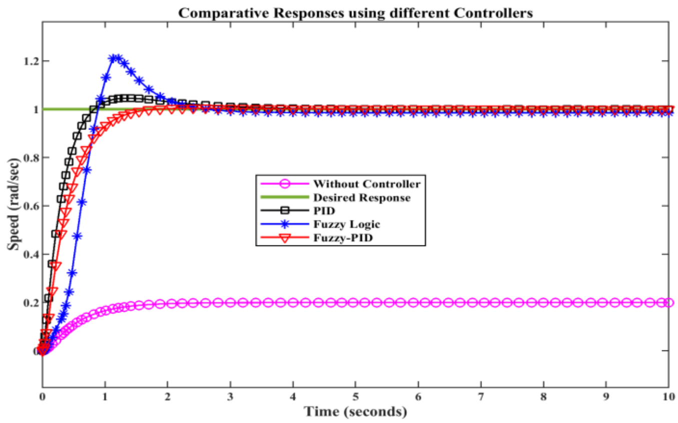

Fig.10 Left wheel velocity of wheelchair using Fuzzy-PID controller

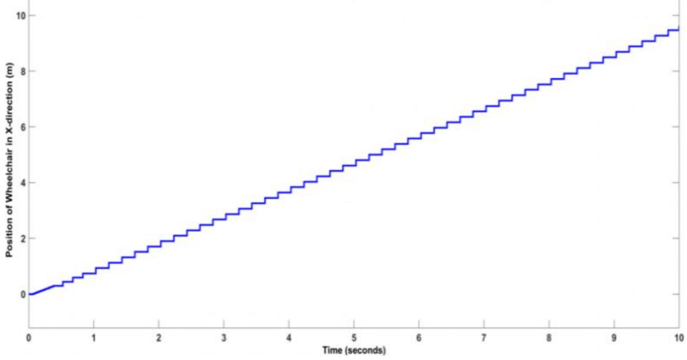

Fig.11 Position of Wheelchair in X-direction using the proposed strategy

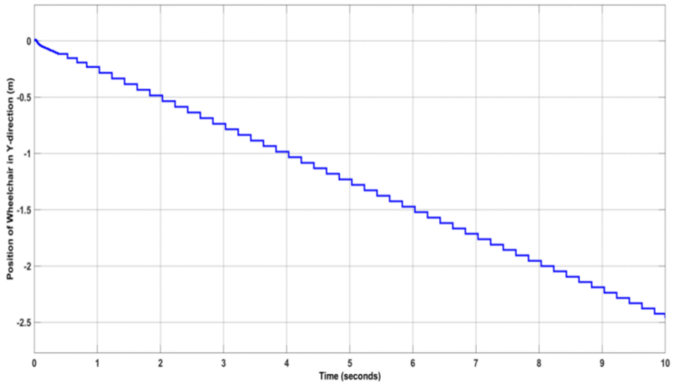

Fig.12 Position of Wheelchair in Y-direction using the proposed strategy

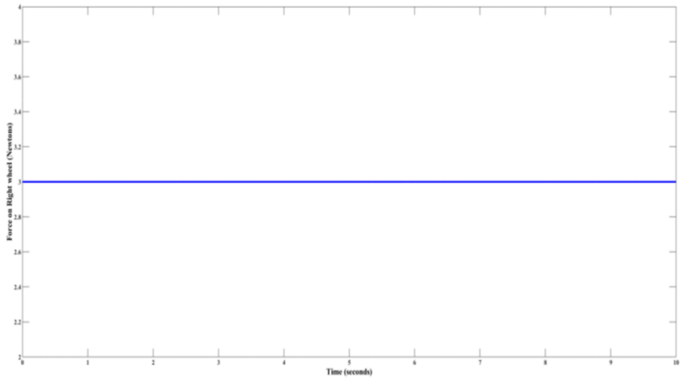

Fig.13 Force on Right wheel of the Wheelchair system

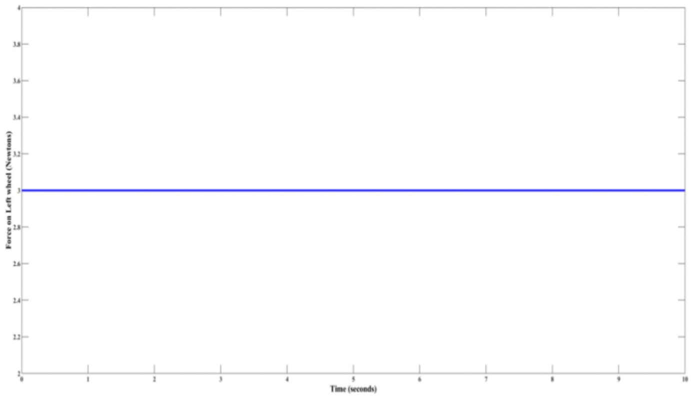

Fig.14 Force on Right wheel of the Wheelchair system

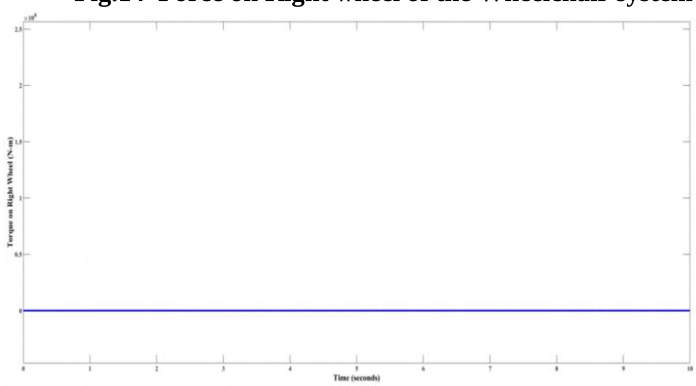

Fig. 15 Torque on Right wheel of the Wheelchair system

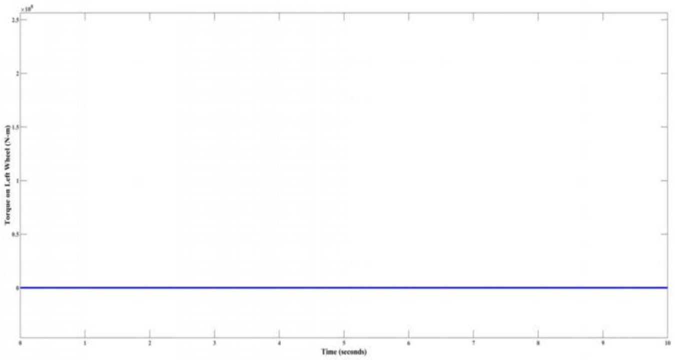

Fig. 16 Torque on Right wheel of the Wheelchair system

Table 3. Performance metrics table

Controller	**Rise-time (t_r)**	**Settling-time (t_s)**	**Overshoot (OS)**	**Steady-state Error (SSE)**	**Desturbance Rejection**
PID	0.5 seconds	3.1 seconds	4%	0%	Significant deviations, slow recovery
Fuzzy-Logic	0.8 seconds	2.8 seconds	20%	0%	Smaller deviations,quicker recovery
Fuzzy-PID	0.75 seconds	2.0 seconds	0%	0%	Minimal deviations, rapid recovery

Conclusion

In this research work, we evaluated the performance of PID, Fuzzy Logic and Fuzzy-PID controllers for the motion control of a smart mobility system. The simulations were conducted in MATLAB/Simulink and the controllers were assessed based on metrics such as rise time, settling time, peak-overshoot, steady-state error and disturbance rejection. The PID controller exhibited a slow rise time and zero steady-state error, indicating its ability to accurately maintain the desired velocity response. It showed significant peak-overshoot and poor handling of dynamic changes and disturbances.The Fuzzy Logic Controller provided a fast response with maximum overshoot and better adaptability to changing conditions. The rise time and the settling time was less compared to the PID controller indicating a more gradual approach in achieving the desired response.The Fuzzy-PID controller achieved a balanced performance, combining the rapid response of the Fuzzy Logic controller with the robustness and smoothness of the PID Controller. It had a fast rise time, reduced overshoot, quick settling-time and excellent disturbance rejection making it the most effective solution among the three control strategies. The main disadvantage of using Fuzzy-PID control strategy is that its design and tuning is more time consuming, requiring extensive knowledge and effort.

Overall, the Fuzzy-PID controller emerged as the most effective control strategy for velocity control in smart mobility systems. It effectively mitigates the limitations of both the PID and Fuzzy Logic controllers, providing a robust and adaptive solution that can handle various operating conditions and disturbances. To further enhance the Fuzzy-PID controller's performance and applicability, future research could focus on the Adaptive and Self-tuning mechanisms, Optimization algorithms like Genetic Algorithms (GAs) or Particle Swarm Optimization (PSO) to fine-tune the fuzzy rule base and membership functions for optimal performance of the system. Future research could also include the hardware implementation to enhance the processing speed and to get the practical notion of the proposed system.

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