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Abstract

Electric vehicles (EVs) are becoming increasingly popular, however, achieving smooth and efficient speed control remains a significant challenge. This paper introduces an innovative approach by proposing an AFUPID (adaptive fuzzy-PID) technique for regulating the speed of EVs utilizing a DC motor. The paper begins by presenting the hardware architecture and modeling of the DC motor within an EV. Subsequently, it critically analyzes the limitations of conventional PID and fuzzy logic control methods. The proposed methodology is an AFUPID controller, which intelligently adjusts PID coefficients based on fuzzy inference mechanisms. Simulation results verify the effectiveness of the AFUPID controller, showcasing a smoother response and reduced errors when compared to standard PID and fuzzy controllers. Furthermore, experimental results validate the exceptional performance of the proposed method in real-world implementation. In essence, this study provides a potential solution for robust adaptive speed control in EVs through the integration of fuzzy inference and PID control, addressing the challenges of achieving optimal speed regulation in EVs.

Keywords (separated by '-')	Electric vehicle - DC motor - PID - Adaptive cruise control - PID-fuzzy logic controller

Design of Adaptive Fuzzy-PID for Adaptive Cruise Control of Electric Vehicle Using DC Motor: Theory and Experiment

Van Du Phan, Van Quyet Phan, Thai Son Dang, Ngoc Hoang Trinh, Phuc Ngoc Nguyen, Ngoc Minh Luong, Ba Uy Nguyen, Quoc Cuong Phan, Ha Phan Bui, Phi Cuong Anh Nguyen, Van Nguyen Phan, and Dinh Thanh Dang

Abstract Electric vehicles (EVs) are becoming increasingly popular, however, achieving smooth and efficient speed control remains a significant challenge. This paper introduces an innovative approach by proposing an AFUPID (adaptive fuzzy-PID) technique for regulating the speed of EVs utilizing a DC motor. The paper begins by presenting the hardware architecture and modeling of the DC motor within an EV. Subsequently, it critically analyzes the limitations of conventional PID and fuzzy logic control methods. The proposed methodology is an AFUPID controller, which intelligently adjusts PID coefficients based on fuzzy inference mechanisms. Simulation results verify the effectiveness of the AFUPID controller, showcasing a smoother response and reduced errors when compared to standard PID and fuzzy controllers. Furthermore, experimental results validate the exceptional performance of the proposed method in real-world implementation. In essence, this study provides a potential solution for robust adaptive speed control in EVs through the integration of fuzzy inference and PID control, addressing the challenges of achieving optimal speed regulation in EVs.

Keywords Electric vehicle · DC motor · PID · Adaptive cruise control · PID-fuzzy logic controller

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1 Introduction

Electric vehicles have emerged as a promising solution to mitigate global carbon emissions from the transportation sector [1, 2]. However, a critical aspect of electric vehicles (EVs) lies in ensuring adaptive speed control for the traction motor under diverse road conditions. Hence, the importance of efficient cruise control systems has a crucial role in enhancing energy efficiency for electric vehicles. This paper focuses on the modeling and adaptive speed control system in EVs.

Two primary kinds of motors are regularly used in EVs: DC motors and induction motors. However, induction motors exhibit strong nonlinearity and difficulties in speed adjustment. Due to their straightforward structure, flexible control capability, high starting torque, and broad speed range, DC motors are deemed more suitable for electric vehicle propulsion systems [3–5]. This paper specifically examines the electric vehicle propulsion system based on a DC motor.

To meet the speed control requirements for electric vehicles, numerous scholars have proposed various methods, including Proportional–Integral–Derivative (PID) controller, backstepping, fuzzy logic, neural networks, and more. Among these, PID controllers and fuzzy logic controllers are recognized as the two primary methods for motor speed control [6–9]. However, conventional methods often suffer from fixed control gains, limiting the output performance of the system. Therefore, this study introduces an AFUPID controller designed to achieve optimal cruise control performance. The AFUPID controller continuously adjusts PID coefficients based on fuzzy inference mechanisms. AQ3

The paper's three main contributions are: First, addressing the modeling and hardware architecture of the EV speed control system. Second, proposing an AFUPID controller tailored for electric vehicle systems. Third, presenting results that demonstrate the superiority of the proposed controller, validated through detailed simulations and experiments.

2 System Implementation

2.1 Hardware Architecture

The hardware design processes aim to maximize flexibility in the surrounding environment for the electric vehicle (EV) model testing, as depicted in Fig. 1. In this paper, the EV model is designed for experimentation in the most stable environment to avoid unwanted external influences.

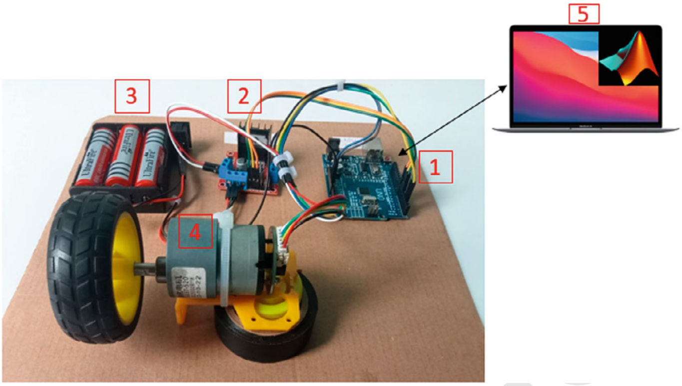


Fig. 1 Hardware platform (1—Arduino Uno, 2—driver L298H, 3—lithium battery, 4—DC motor integrated encoder, 5—PC)

The fundamental components of the EV model testing include one Arduino board corresponding to a central controller, one L298 H-bridge circuit corresponding to a power converter, a 12 V power supply derived from three lithium polymer (LiPo) cell batteries, each LiPo cell with a voltage capacity of 3.7 V. It is noted that a JGB37-520 gearbox motor equipped with an encoder to feedback speed signal, ensuring the stable and precise control of the motor as well as the wheel of EV. Lastly, a USB connecting cable is employed for communication between the personal computer (PC) and Arduino to control the system. All hardware connections are made through specialized connectors to enhance system stability and flexibility. The block diagram of the EV model testing is presented in Fig. 2.

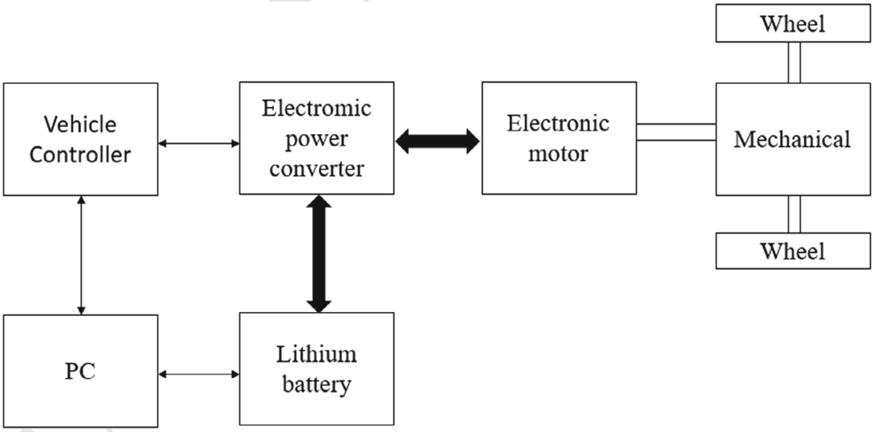


Fig. 2 Block diagram of EV model testing

Table 1 Specifications of the DC motor

Parameters	Value	Parameters	Value
Voltage constant (k_t, K_e)	0.02 Nm/A	Inductance (L)	0.5 H
Inertia motor (J)	0.01 kg m^2/s^2	Factor of friction (b)	0.1
Resistance (R)	2 Ω		

2.2 Modeling of the DC Motor

In this section, the mathematical model of the DC motor is represented as follows [5]:

$$\begin{aligned} \frac{\mathrm{d}^2\theta}{\mathrm{d}t^2} &= \frac{1}{J}\left(k_t i - b\frac{\mathrm{d}\theta}{\mathrm{d}t}\right) \\ \frac{\mathrm{d}i}{\mathrm{d}t} &= \frac{1}{L}\left(-Ri + v - K_e\frac{\mathrm{d}\theta}{\mathrm{d}t}\right) \end{aligned} \quad (1)$$

where J, b, k_t, and K_e are inertia torque, the coefficient of friction of mechanical components, positive gains, respectively. R, L, v, and i are the resistance of the winding wire, the coefficient of self-inductance, the voltage applied and the current flowing to the motor coil, respectively. θ is the position of the rotational axis.

From the constructed DC electric motor model above, the specifications of the motor model are presented in Table 1.

3 Control Design

In this section, a AFUPID controller is formulated to enhance control quality which will be compared with two other controllers, namely, fuzzy logic controller (FLC) and PID. The overview speed adjust system diagram is illustrated in Fig. 3.

3.1 PID Controller

The PID controller is constructed to regulate the speed of the motor then change the speed of EV's wheels. The control effort of PID can be formulated as follows:enlargethispage40pt

$$u(t) = K_p e(t) + K_i \int_0^t e(t)\mathrm{d}t + K_d \frac{\mathrm{d}e(t)}{\mathrm{d}t} \quad (2)$$

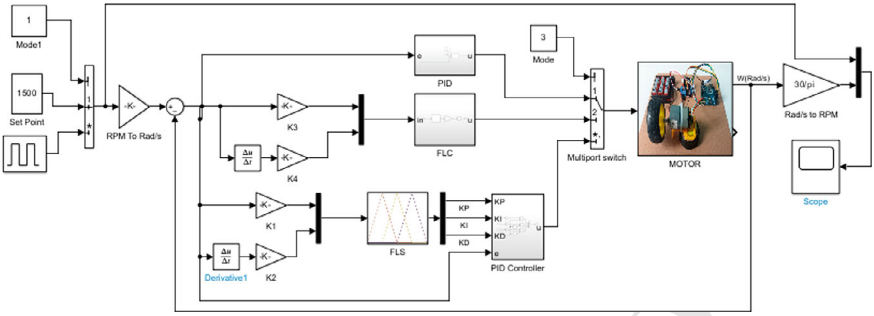


Fig. 3 Block diagram of AFUPID control system for DC motor control

where $e(t)$ is the tracking error. K_p, K_i, and K_d is the designed gain.

3.2 Fuzzy Logic Controller

The FLC is designed to regulate the speed of the motor that utilizes the Mamdani approach. It is constructed with one output (u) and two inputs (e, de). The membership functions (MF) for the inputs consist of 5 triangle MFs with the standard input range [− 1; 1], known as, Positive Big (PB), Positive Small (PS), Zero (ZE), Negative Big (NB), and Negative Small (NS). The outputs consist of 7 triangle MFS, known as, Positive Large (PL), Positive Medium (PM), Positive Small (PS), Zero (ZE), Negative Large (NL), Negative Medium (NM), and Negative Small (NS). The fuzzy MFs for the inputs and outputs are described in Fig. 4.

In this study, the control rule table for the FLC is presented in Table 2.

3.3 AFUPID Controller

The focal point of this study is to construct a AFUPID controller, a combination of the two controllers introduced above. The controller will be designed with 2 inputs and 3 outputs, where two inputs (e, de), and the three outputs correspond to the parameters of Δk_p, Δk_i, Δk_d to be fed into the PID controller in Eq. (2). The MFs for the inputs consist of Positive Big (PB), Positive Small (PS), Zero (ZE), Negative Big (NB), and Negative Small (NS). The outputs consist of 7 MFs: Very Large (VL), Medium Large (MLa), Large (L), Medium (M), Medium Low (ML), Low (L), and Very Low (VL). The fuzzy MFs for the inputs and outputs are illustrated in Figs. 5 and 6.

Then the following equations to calculate the control gains K_p, K_i, and K_d in Eq. (2) is expressed by:

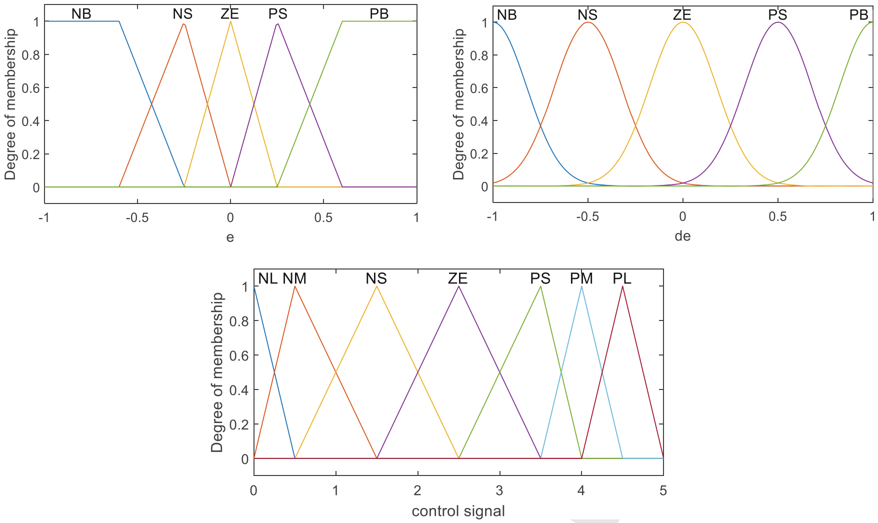


Fig. 4 MFs of two inputs (*e* and *de*) and output (control signal) of the FLC

Table 2 Control rules for FLC

u		*e*				
		NB	NS	ZE	PS	PB
de	NB	NL	NL	NM	NS	ZE
	NS	NL	NM	NS	ZE	PS
	ZE	NM	NS	ZE	PS	PM
	PS	NS	ZE	PS	PM	PL
	PB	ZE	PS	PM	PL	PL

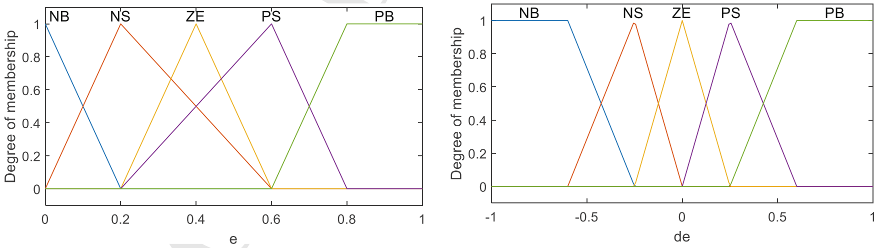


Fig. 5 MF of the inputs (*e* and *de*) of the AFUPID controller

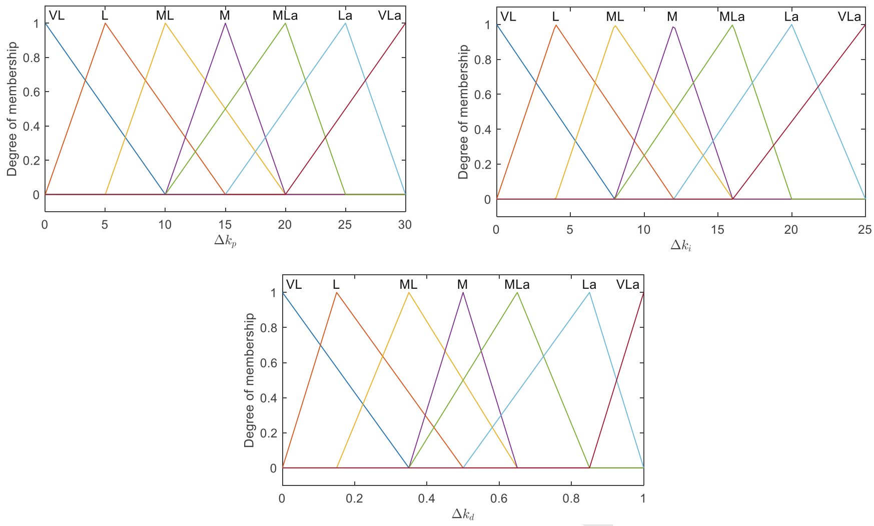


Fig. 6 MFs of the output (Δk_p, Δk_i, Δk_d) of the AFUPID controller

$$\Delta k_j = \frac{K_j - K_{j\,\min}}{K_{j\,\max} - K_{j\,\min}}, \quad j = p, i, \text{ and } d. \tag{3}$$

The ranges of K_j ($j = p$, i, and d) are $[K_{j\,\min}, K_{j\,\max}]$. The control rule table for the AFUPID controller is presented in Tables 3, 4, and 5.

Table 3 Rules applied in the PID controller for K_p

e/*de*	NB	NS	ZE	PS	PB
NB	VLa	VLa	VLa	VLa	VLa
NS	MLa	MLa	MLa	La	VLa
ZE	VL	VL	L	ML	ML
PS	MLa	MLa	MLa	La	VLa
PB	VLa	VLa	VLa	VLa	VLa

Table 4 Rules applied in the PID controller for K_i

e/*de*	NB	NS	ZE	PS	PB
NB	M	M	M	M	M
NS	ML	ML	ML	ML	ML
ZE	L	L	PVS	L	L
PS	ML	ML	ML	ML	ML
PB	M	M	M	M	M

Table 5 Rules applied in the PID controller for K_d

e/*de*	NB	NS	ZE	PS	PB
NB	VL	ML	M	La	VLa
NS	ML	MLa	La	VLa	VLa
ZE	M	La	La	VLa	VLa
PS	MLa	VLa	VLa	VLa	VLa
PB	VLa	VLa	VLa	VLa	VLa

In this study, the “centroid” approach is utilized for defuzzification stage to achieve K_p, K_i, and K_d, that are fed to the PID controller and using Eqs. (2) and (3) to regulate the DC motor of the EV.

4 Main Result

4.1 Simulation Result

To validate the effectiveness of the suggested method, the simulation and experiment studies were conducted in the MATLAB environment. In the modern EV, the function of adaptive cruise control has appeared. The driver can select several options of this function such as tracking preset speed and tracking the previous EV on the road. Hence, in this study, the motor speed driven for EV was set according to two cases. Case study 1 presents the output response following the constant speed which utilizes a constant block in MATLAB Simulink and set to 450 [rpm]. Case study 2 employed a square wave block with a maximum value of 500 [rpm] and a pulse width of 50% that illustrates the tracking the previous EV. The response plots for the three controllers (PID, fuzzy controller, and proposed controller) are displayed in Figs. 7 and 8.

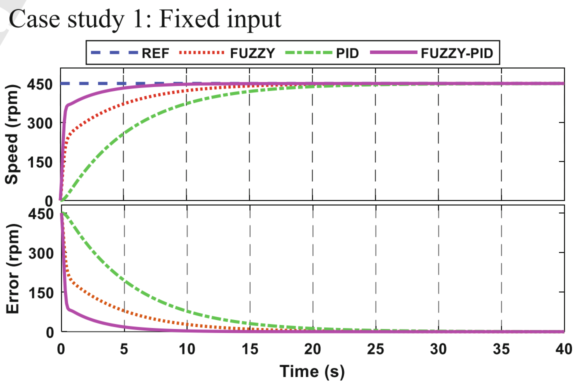
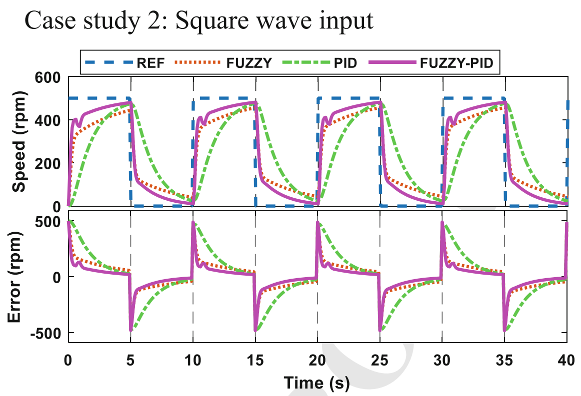


Fig. 7 Simulation results of the fixed input signal

Fig. 8 Simulation results of the square wave input signal

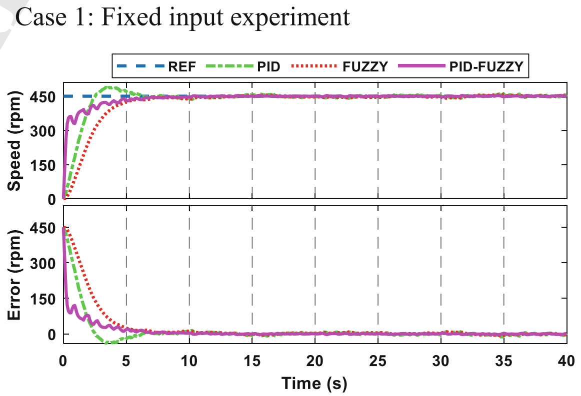

Case study 2: Square wave input

From Fig. 7, it can be observed that the PID has the worst performance as compared to other controllers because of the fixed control gains. The self-tuning control gain by combining the PID and fuzzy logic technic make the best performance of the suggested controller. From Fig. 8, we can see that the output speed responses of the PID and fuzzy become poor when the reference signal has significant change. Meanwhile the suggested controller still brings the better tracking performance as compared to relevant controller.

4.2 Experiments Results

To evaluate the efficiencies of the proposed algorithm, the experiment trials are studied. During the experimental, the desired speed of two case studies are the same with in the simulation section. Hence, the response and tracking errors graph of the experimental phase are displayed in Figs. 9 and 10.

Fig. 9 Experiment results of the fixed input signal


Case 1: Fixed input experiment

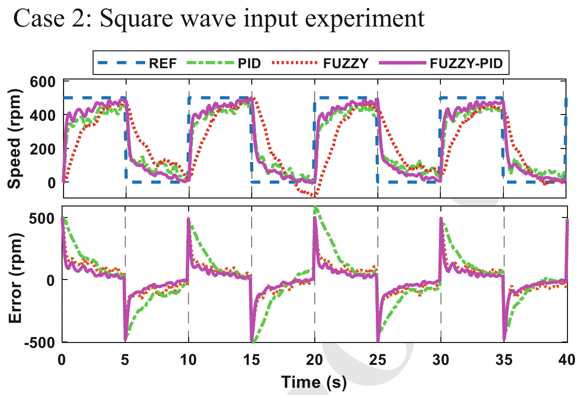


Fig. 10 Experiment results of the square wave input signal

From the results of Figs. 9 and 10, it is evident that big transient, overshoot, and rise time are achieved by the other two methods. Meanwhile, the quality of the suggested method achieves the best performance. The suggested algorithm guarantees that the tracking error has not overshoot and satisfactory performance is obtained. It provides the output speed nearest to the desired signal. The reason is that it combines the advantage of two separate technique, namely the PID and the fuzzy logic technique. Consequently, the proposed controller demonstrates accuracy, paving the way for new advancements in the EV applications.

5 Conclusion

In this article, a description of the hardware and software system of an EV model has been presented to implement adaptive cruise speed control through various control approach. In the suggested methodology, the gains of the PID are adjusted utilizing fuzzy logic methods. The study demonstrates that the AFUPID achieves both the accuracy of a traditional PID controller and the flexibility of a fuzzy logic controller. Simulation and experimental results exhibited that the suggested control strategy obtains good control performance for the DC motor applied in EV with accurately tracking speed, a fast response time and no overshooting. The steady-state error is decreased to zero, indicating better efficiency compared to other presented controllers.

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