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A Novel Real-Time Robust Controller of a Four-Wheel Independent Steering System for EV Using Neural Networks and Fuzzy Logic

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Abstract: In this study a four-wheel independent steering (4WIS) system for an electric vehicle (EV) steered by stepper motors is presented as a revolutionary real-time control technique employing neural networks in combination with fuzzy logic, where the use of the neural network greatly simplifies the computational process of fuzzy logic. The control of the four wheels is based on a variation of a Hopfield Neural Network (VHNN) method, in which the input is the error of each steering motor and the output is processed by a hyperbolic tangent function (HTF) feeding the fuzzy logic controller (FLC), which ultimately drives the stepper motor. The whole system consists of the four aforementioned blocks which work in sync and are inseparable from each other with the common goal of driving all the steering stepper motors at the same time. The novelty of this system is that each wheel monitors the condition of the others, so even in the case of the failure of one wheel, the vehicle does not veer off course. The results of the simulation show that the suggested control system is very resilient and workable at all angles and speeds.

Keywords: four-wheel independent steering; steer-by-wire; electric vehicles; steering geometry; stepper motor; neural network; fuzzy logic

MSC: 93-08

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1. Introduction

EVs are gaining popularity as a means of reducing environmental pollutants and combating climate change. One of the challenges in electrification is integrating Brushless Direct Current (BLDC) electric motors into the wheels for direct transmission to all four wheels, eliminating the need for intermediate gears and other friction-inducing components that decrease efficiency. Additionally, Steer-by-Wire (SBW) technology represents a major advance in the steering system by removing any mechanical links between the steering wheel and the driving wheels.

Therefore, it is essential to focus on researching a control strategy that maximizes the benefits of the independent four-wheel steering system. Numerous researchers have made significant progress in the design and management of these systems for EVs. For instance, Furukawa et al. [1] describes critical aspects of 4-wheel steering (4WS) technology and control methods, providing an overview and perspective on related research fields. Shibahata et al. [2] discuss the development of a 4WS vehicle with electronically controlled rear wheels, enhancing fundamental dynamic features by maintaining a side-slip angle of zero at the center of gravity. Sano et al. [3] create a controller to achieve a side-slip angle of zero at a steady state, while Hongyu et al. [4] propose an optimization control method based on steering center coincidence to improve driving performance and address issues like tire wear and unharmonious vehicle movement. Moreover, a novel approach for full-speed optimal Ackermann angle allocation aiming to enhance steering stability and reduce tire wear is presented in [5].

For four-wheel independent-drive electric vehicles (4WIDEVs), Yin et al. [6] focus on global yaw moment generation and a torque distribution management system, considering tire consumption and yaw moment effectiveness for improved stability and handling. Fuzzy control theory is used in [7,8] to establish controllers determining the rear wheel steering angle based on the influence of the front wheel steering angle and speed, effectively reducing side-slip angle, yaw rate, and roll angle peaks. Furthermore, Tian et al. [9] investigate skid steering and differential steering of 4WIDEVs, particularly in cases of steering failure. Özatay, in [10], introduces a fuzzy logic controller integrating the driver's steering input with the 4WS system, achieving a body side-slip angle of zero and ensuring a quick response of the yaw rate. Haytham et al. [11] design an optimally tuned PID controller for steering control of a 4WS vehicle using a genetic algorithm. Additionally, Ariff et al. [12] provide a four-wheel active steering system with a model-following control structure, enhancing dynamic behavior through feedforward and feedback compensation algorithms. Khan et al. [13] utilize the robust H control approach to examine a robust differential steering control system for a 4WIDEV. To improve vehicle performance under various working situations, Zhou et al. [14] propose a multi-mode optimum decision control system based on the vehicle's linear 2-DOF dynamic model. Arifin et al. [15] propose a novel method for the steering control of autonomous vehicles, based on type 2 fuzzy logic control combined with PI control, by limiting the maximum speed limit to 40 km/h. A predictive controller based on a tracking error model, unrestrained on the front and rear wheels' steering relationship of the 4WS vehicle, which controls the lateral deviation of the vehicle and corrects it through a PI controller by tracking the path of the vehicle, is proposed by Tan et al. [16]. The advantage of this controller is that it can fully utilize the steering freedom, but it is limited to very low speeds. Finally, Jeong et al. [17] present a method to design an integrated path-tracking and lateral stability controller for an autonomous 4WIDEV on low-friction roads.

To address the current challenges in the field of EVs, this paper proposes:

✓ A novel real-time robust controller for a 4WIS system in EVs with stepper motors, employing neural networks and fuzzy logic.
✓ The proposed control system, being decentralized, offers advantages such as enhanced stability and reduced complexity. In this system, each motor's motion takes into account the position of other motors, ensuring stability and robustness.
✓ Through an optimized control strategy, the system achieves smoother and more coordinated steering motions, resulting in improved vehicle handling and reduced stress on tires [4,5].

Furthermore, an additional advantage explored in this study is the ability to precisely control the driving forces applied to the steering wheels, effectively serving as a power steering mechanism. This application offers the opportunity to make traditional hydraulic motor steering systems or electric direct drive systems redundant. As a result, the system is simplified, while saving the energy normally consumed by conventional steering. Consequently, the energy consumption is optimized, and the proposed system leads to an improved overall performance for 4WIS [18].

Neural networks and fuzzy logic are both powerful tools in control systems that tackle complex problems and make intelligent decisions. Importantly, they are not mutually exclusive and can be used together in hybrid systems to comprehensively tackle complex control problems [19]. For example, Zhang Qi et al. [20] designed a neural network fuzzy energy management strategy for hybrid EVs based on driving cycle recognition. Even if the specific system does not heavily rely on data-driven learning, neural networks can be utilized for tasks such as motor control or mapping sensor inputs to desired steering outputs. In addition, the use of a neural network simplifies the computational power required by the fuzzy logic algorithm, as shown in the corresponding section below.

The performance of the control system is evaluated using numerical simulations on the Matlab/Simulink platform. The proposed control method was subjected to simulation tests, introducing random wheel-position errors into a neural network based on the Hopfield networks idea. The neural network weights were chosen to ensure equal contribution from each wheel to the error calculation. Tests were performed with different activation functions in the neural network, with the Tan-sigmoid function proving to be optimal. The error was then converted and fed into a simple fuzzy logic algorithm commanding the driver of each motor.

Compared to other papers, the proposed control system offers several advantages:

- Increased stability and robustness, since the positions of the stepper motors are considered during motion.
- Simplifies the computational power needed by the fuzzy logic algorithm (only one input and four rules are needed) using a neural network compared to other similar works in which fuzzy logic is applied [7,8,10,14,15].
- In contrast to centralized control systems [6,7,10–17], the proposed method provides greater stability and improved steering performance.
- Simulation test results demonstrate that the proposed control system can optimally drive the stepper motors simultaneously, following the control rules for different angles and speeds of the vehicle, demonstrating high robustness and practicality.
- Each wheel "listens" to the others, so, in the event of a fault in one wheel, the vehicle adjusts the angles of the rest wheels in order to avoid the derail of the EV, a condition that is not addressed in techniques presented in related papers in the literature [4–18].

In conclusion, the proposed real-time robust controller is a significant development in electric vehicle control systems. Its novel features provide advantages over existing systems, offering high stability, energy efficiency, and practicality.

The remainder of the article is structured as follows: Section 2 introduces the theory and the calculation of the four-wheel steering geometry for each wheel. In Section 3 the mathematical modeling of a hybrid stepper motor and the parameters of the stepper motor under consideration is presented. In Section 4 the real-time control strategy for a 4WIS system in EVs with stepper motors using neural networks combined with fuzzy logic is proposed, while Section 5 presents simulation results and analysis, followed by the Conclusions in Section 6.

2. Steering Geometry Calculations

In 4WS vehicles, the relationship (k) between rear and front wheels' steering angles (δ_{rear} and δ_{front}, respectively) relies on the vehicle's speed (U) and is given in the diagram shown in Figure 1 [3].

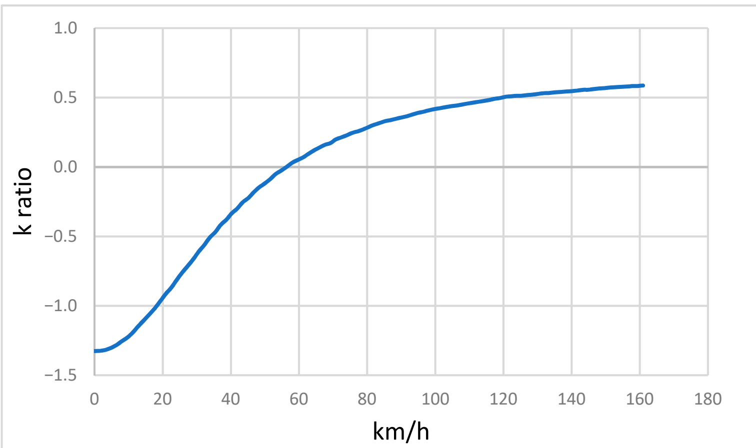


Figure 1. k ratio in relation to vehicle speed.

When moving slowly, the rear wheels are directed in the opposite direction to the front ones. The front and rear wheels revolve in the same direction when traveling at high speed.

The input angle, determined by the driver of the vehicle or, in the case of autonomous driving, by the software, is regarded as the front axle's center angle (δ_{front}). The entrance angle ranges between $-45^\circ \leq \delta_{front} \leq 45^\circ$ while driving normally (not while parking or doing a zero turn). In the four graphs illustrated in Figures 2–5, the angle of each wheel, depending on the speed of the vehicle and the angle of the steering command are presented. The graphs' calculation is based on the equations presented in reference [21] and is performed for angle values ranging from 5 to 45 degrees, with an increment of 5 degrees, and velocities ranging from 5 to 100 km/h, with 5 km/h increments.

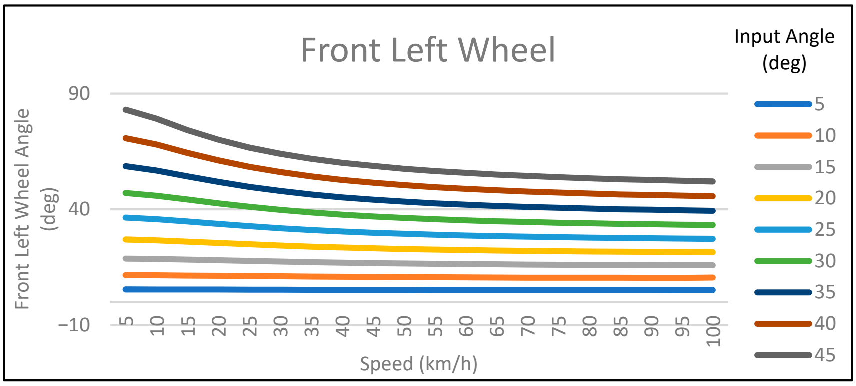


Figure 2. Front left wheel angle.

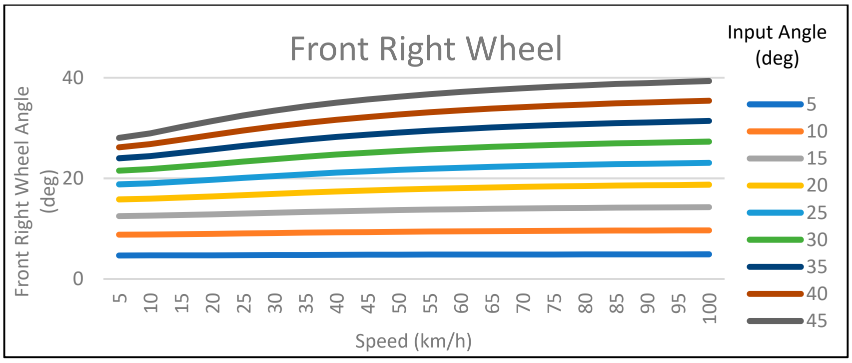


Figure 3. Front right wheel angle.

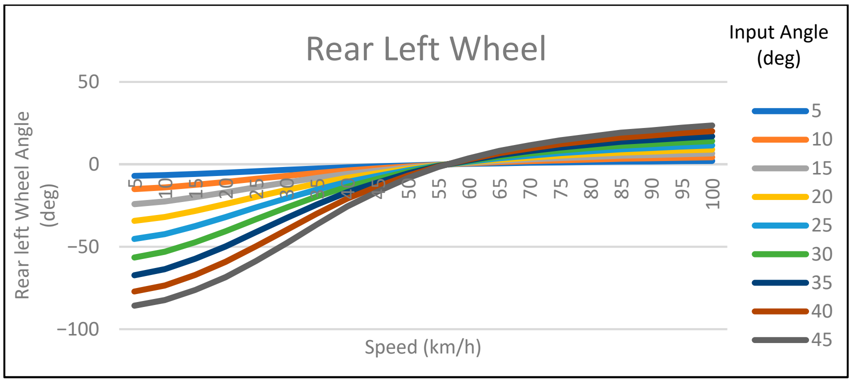


Figure 4. Rear left wheel angle.

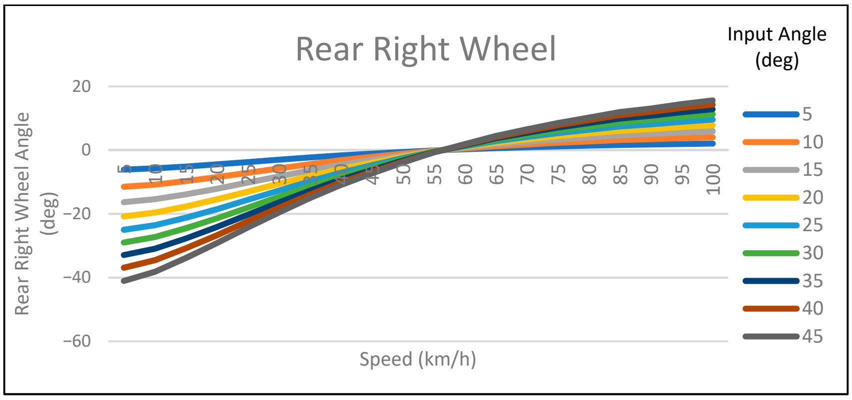


Figure 5. Rear right wheel angle.

Figures 2–5 clearly show how the angle of each wheel varies as a function of the vehicle's input angle and its corresponding velocity. Up to a speed of 56.33 km/h, the rear wheels move in the opposite direction to the front wheels; while exceeding this threshold, all wheels have the same direction of rotation. Furthermore, it can be observed that at low speeds and with a large input angle (>30 deg), the wheels exhibit significant divergence relative to the input angle, a phenomenon that diminishes as the speed or the input angle decreases.

3. Mathematical Modelling of a Hybrid Stepper Motor

Hybrid stepper motors are a variant of modern permanent magnet motors with two phases, phase A and phase B, which are perpendicular to each other, and their mutual inductance is zero [8]. Equations (1) and (2) represent the basic electrical equations for the hybrid stepper motor:

$$u_a = Ri_a + L\frac{di_a}{dt} - K_m\omega\sin(N\theta) \tag{1}$$

$$u_b = Ri_b + L\frac{di_b}{dt} - K_m\omega\cos(N\theta) \tag{2}$$

where i_a and i_b are the currents of phases A and B (A), u_a and u_b are the phase voltages (V), R is the phase resistance (Ω), L is the phase inductance (H), K_m is the torque constant (V·s/rad), ω is the angular velocity (rad/s), θ is the mechanical rotor position (rad), and N is the rotor number teeth.

The mechanical equations of the hybrid stepper motor are expressed in Equations (3) and (4).

$$K_m(-i_a\sin(N\theta) + i_b\cos(N\theta)) - T_L = J\frac{d\omega}{dt} + K_v\omega \tag{3}$$

$$\omega = \frac{d\theta}{dt} \tag{4}$$

where K_v is the coefficient of viscous friction (N·m·s/rad), J is the system inertia (kg·m^2), and T_L is the load torque (N·m).

The hybrid stepper motor's simulation-related parameters are provided in Table 1.

Table 1. Stepper motor parameters.

Phase Number	2
Inductance of Winding (H)	1.4×10^{-3}
Resistance of Winding (Ohm)	0.7
Angle of Step (degree)	1.8
Max Flux Linkage (Vs)	0.005
Max Detent Torque (N·m)	0.002
Total inertia (kg·m·m)	1.2×10^{-7}
Total friction (N·m·s)	1×10^{-4}

4. Controller Design Strategy

The hybrid stepper motor controller is responsible for the simultaneous rotation of all wheels to their final position according to the central command of the vehicle's steering system. The requirement in such a system is the interaction of all the wheels with each other and, by extension, of course, with the central command. Consequently, during operation each wheel must rotate at the angle assigned to it, but also "listen" to the state of the other wheels.

The control system presented in this paper combines techniques derived from the fields of neural networks and fuzzy logic. One important component of neural networks is the activation function, which maps the input to a non-linear output that is used to determine the activation level of the neuron. Here, after applying the trial-and-error process several times, the hyperbolic tangent function is chosen to be used as the activation function in the neural network in order to classify the error values into a range between −1 and 1. Furthermore, the slope of the hyperbolic tangent function with parameter the coefficient k is plotted, as shown in Figure 6.

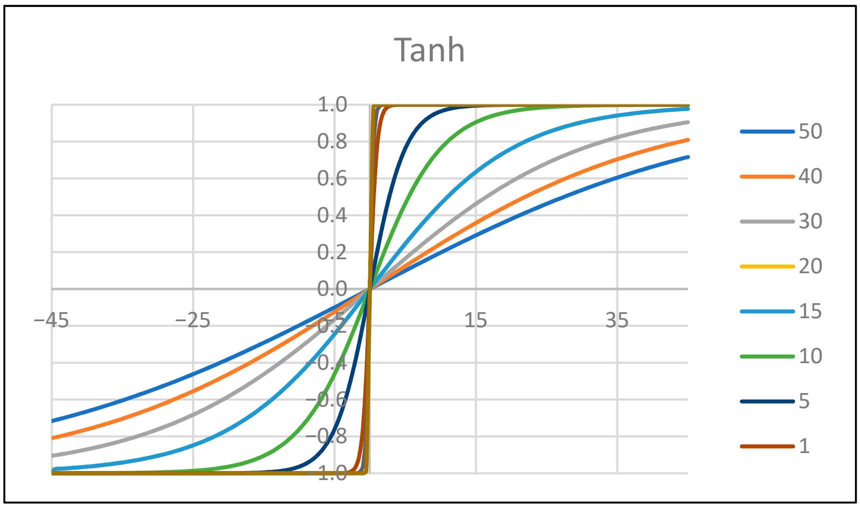


Figure 6. Tangent function according to k value.

Fuzzy logic process, on the other hand, relies on the concepts of fuzzification and defuzzification to deal with data imprecision [22–24] as shown in Figure 7. Fuzzification involves mapping continuous input values to a set of fuzzy values or membership functions that describe the degree of membership of the input to each fuzzy set. In order to help the system deal with the data's imprecision, the location error is fuzzified in this paper. The resulting fuzzy sets are then used to determine the degree of activation of each rule in the rule base.

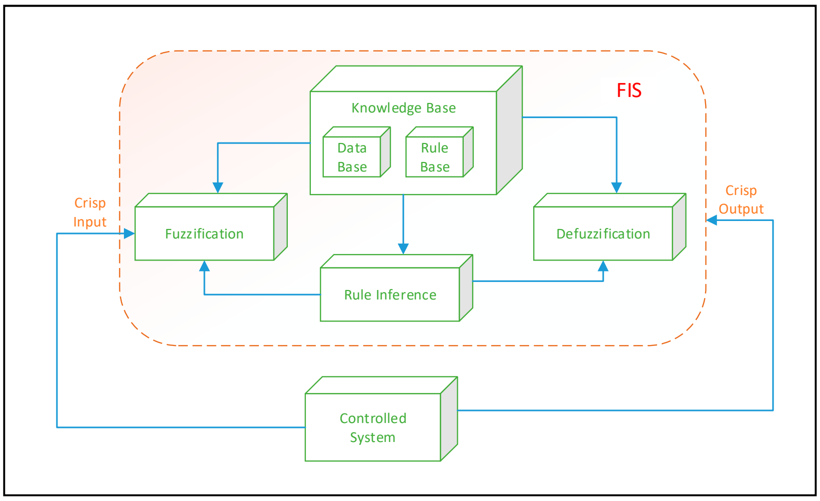


Figure 7. Fuzzy logic process [22–24].

Defuzzification is the process of mapping fuzzy values to a crisp value that can be used to control the system. In this work, the output of the fuzzy logic function is defuzzified using the Mamdani method [22], which involves combining the outputs of all the activated rules using a weighted average. The resulting crisp value is used to control the stepper motor and ensure that each wheel rotates at the angle to which it is assigned, while also "listening" to the state of the other wheels.

Overall, the control system, having imprecise inputs and outputs with non-linear relationship between them, can operate effectively in a complex and unpredictable environment, thanks to the integration of fuzzy logic and neural networks. The activation function in the neural network provides a non-linear mapping of the input that can capture the complex relationships between the input and output, while the fuzzy logic function provides a set of rules that can deal with the imprecision and uncertainty of the data. The use of defuzzification, using the Mamdani method, ensures that the resulting crisp value can be used to control the system and ensure the simultaneous rotation of all wheels to their final position according to the central command of the vehicle's steering.

The control strategy is depicted in Figure 8 in more detail. More specifically, the vehicle steering command θi is sent to all motor controllers where the vehicle angle is converted into wheel angles (θi_{FL}, θi_{FR}, θi_{RL}, θi_{RR}) according to Section 2. The desired angle of each wheel is then compared with the output of the corresponding stepper motor (θo_{FL}, θo_{FR}, θo_{RL}, θo_{RR}) and the error (θe_{FL}, θe_{FR}, θe_{RL}, θe_{RR}) is obtained.

All of the neural networks receive feedback from the resultant errors. The error of the motor of interest is multiplied by one while the resulting errors of the other motors are multiplied by $-1/3$ (in order to take under consideration, the average error derived from the other controllers). Thereinafter, the result is fed into the hyperbolic tangent function f(error) (5). The coefficient k was chosen after several simulation tests, taking into account Figure 6 and the desired response of the fuzzy logic controller. As shown in Figure 6, for low values of k, the tanh function becomes rigid and the error fed to the fuzzy logic controller tends to have a stiff response for small angle errors (i.e., for small angle errors the fuzzy logic unit is fed by the maxi-mum allowable error value), while for higher values of k, the error fed to the fuzzy logic controller exhibits better scalability. However, if the value of k is too high, the desired response is too slow. Therefore, the value of k should be chosen carefully. In the following results k = 5 was chosen, considering Figure 6 and the abovementioned "restrictions".

$$\mathrm{f(error)} = \frac{\mathrm{e}^{\mathrm{kx}} - \mathrm{e}^{-\mathrm{kx}}}{\mathrm{e}^{-\mathrm{kx}} + \mathrm{e}^{\mathrm{kx}}}, -1 < \mathrm{f(error)} < 1 \tag{5}$$

The result of f(error), which varies, due to the nature of the function, between −1 and 1, is fed into $\text{MAP}(\text{f}_{\text{error}})$ (6) and the function is adjusted to the limits between 0 and 1.

$$\text{MAP}(\text{f}_{\text{error}}) = \frac{\text{f(error)} + 1}{2}, 0 < \text{MAP}(\text{f}_{\text{error}}) < 1 \tag{6}$$

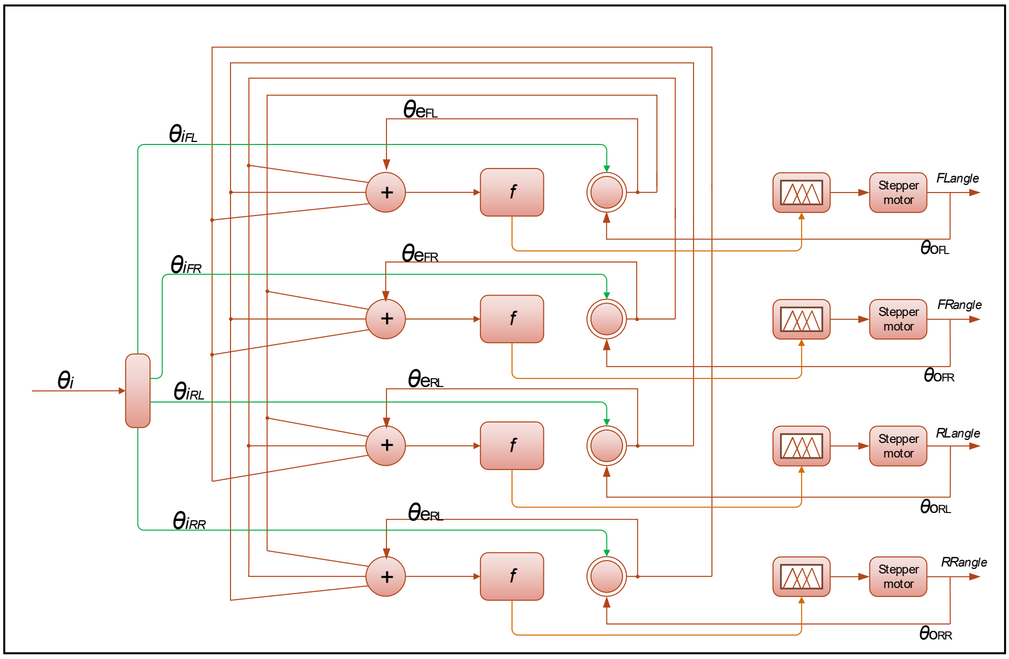
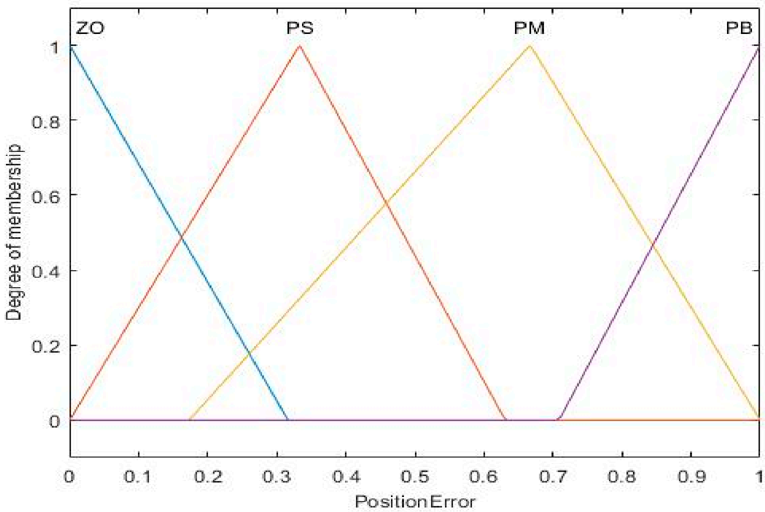


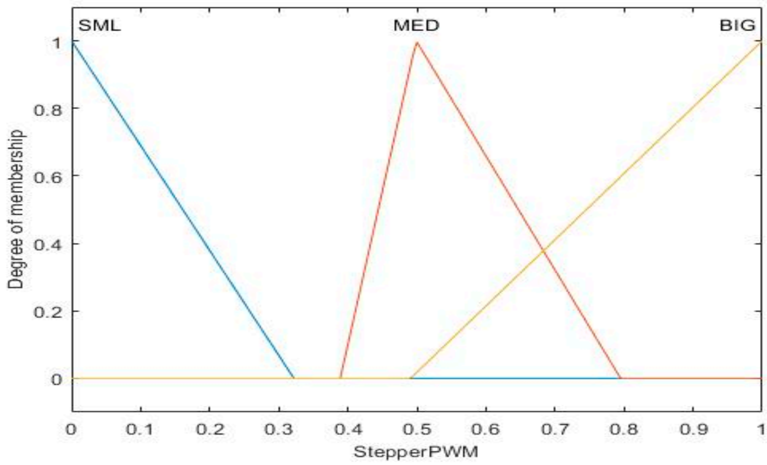
Figure 8. Control block diagram.

The output of $\text{MAP}(\text{f}_{\text{error}})$ then feeds the simple fuzzy logic function, where the input (PositionError) and output (StepperPWM) membership functions and rule base for the Stepper motor control are shown in Figure 9a–c. The PositionError and StepperPWM are normalized from 0 to 1.



(**a**)

Figure 9. *Cont.*



(**b**)

Stepper PWM/Position Error	SML	MED	BIG
ZO	X		
PS	X		
PM		X	
PB			X

(**c**)

Figure 9. (**a**) Input variable "PossitionError"; (**b**) Output variable "StepperPWM"; (**c**) Rule-based control.

It is noted that, in the above fuzzy logic function the control is only performed for positive wheel angles. This is due to the fact that, in the case of negative angles, the corresponding absolute value of the output (StepperPWM) digitally changes the steering of the wheel in the negative direction.

5. Simulation and Results

The proposed control method aims to achieve a specific angle for each wheel simultaneously, indicating a desired motion. For the purpose of this study, and in order to validate the proposed control strategy, indicative representative combinations of vehicle wheel angles and speeds are selected. The logic used to select the angle and speed combinations in Table 2 is based on the fact that the higher the speed, the smaller the steering angle the vehicle can have, and the lower the speed, the larger the steering angle can be. Taking this into consideration, input angles of 5, 15, 25, and 35 degrees in combination with speeds of 5–50–100 km/h, 5–40–75 km/h, 5–25–50 km/h, and 5–15–25 km/h are chosen, respectively. The combination of these values is summarized in the first two columns of Table 2, while the next four columns present the individual angles of the four wheels, as derived from the graphs in Section 2.

The Matlab/Simulink simulation block, presented in Figure 10, consists of four Hybrid Stepper Motors connected to their drivers, supplied by a 24 V battery, with a load applied to each one. The output angle of each motor is fed to an adder, where it is subtracted from the desired angle (step input) to calculate the error. This error is used as the input for all four neural networks, and is multiplied by 1/3 if it is not the motor being controlled, or by −1 if it is. The sum of the multiplied results is further multiplied by the coefficient k = 5 and then processed through a block, where functions (5) and (6) of Section 4 are implemented. The absolute value of the result serves as the input for the fuzzy logic controller. The saturated fuzzy logic output is multiplied by the error if it is positive, and is then used to adjust the duty cycle of the PWM block. Additionally, the frequency of the PWM block is set to 1 kHz. PWM controls the stepper motor driver, which subsequently adjusts the stepper motor to the desired angle. The step response results depicted in Figures 11 and 12 provide insights into the system's behavior under constant load conditions (0.1 Nm) on each motor. The simulation results, for the values in Table 2, allow us to confirm the accuracy with which the control method maintains the desired angles for each wheel.

Table 2. Simulation test parameters.

Input Angle (deg)	Vehicle Speed (km/h)	Front Left Angle (deg)	Front Rear Angle (deg)	Rear Left Angle (deg)	Rear Right Angle (deg)
5	5	5.36	4.69	−6.97	−6.10
5	50	5.17	4.84	−0.61	−0.57
5	100	5.09	4.92	2.13	2.06
15	5	18.68	12.51	−24.09	−16.35
15	40	16.92	13.46	−3.70	−4.57
15	75	16.05	14.08	3.85	3.35
25	5	36.42	18.82	−45.24	−24.99
25	25	34.72	19.36	−37.43	−21.21
25	50	32.72	20.10	−26.12	−15.61
35	5	58.62	24.00	−67.25	−32.92
35	15	54.21	25.09	−57.27	−27.71
35	25	49.71	26.47	−41.17	−20.26

The block diagram of the model, developed using the Matlab/Simulink version 2021a simulation software in order to confirm the theoretical hypothesis, is presented in Figure 10.

The simulation results of the proposed system, obtained by applying the same load on each wheel, are shown in Figures 11 and 12. By inspecting the previous figures, it can be seen that for any input steering angle-vehicle speed combination shown in the first two columns of Table 2, the angle of each wheel (rear and front) reaches the desired value calculated and shown in the last four columns of Table 2, simultaneously. In more detail:

- Step response for angle = 5 deg and velocity = 5 km/h: the difference in angles between all wheels is small, in the order of 1 to 2 degrees. Rotation starts almost simultaneously, but there is a small lag in the front wheels of 0.5 ms, and a small ringing is observed before the steady state. The steady state is reached in about 2.5 ms.
- Step response for angle = 5 deg and velocity = 50 km/h: the difference in angle between the front wheels is very small, which is also true for the rear wheels. The angle difference between the front and rear wheels is about 4.5 degrees. The rotation starts almost simultaneously, but there is a slight lag in the rear wheels of 0.5 ms, and there is ringing before the steady state. The steady state is reached in about 2.5 ms.
- Step response for angle = 5 deg and velocity = 100 km/h: the difference in angle between the front wheels is very small, which is also true for the rear wheels. The difference between the front and rear wheels is about 3 degrees. The rotation starts almost simultaneously, and a ringing is observed before the steady state. The steady state is reached in about 2.5 ms.
- Step response for angle = 15 deg and velocity = 5 km/h: the difference in wheel angles has a constant deviation of about 6 degrees from wheel to wheel. The start of rotation shows a lag of 0.5 ms from wheel to wheel. A small ringing (much smaller than the 5 deg case) is observed before the steady state. The steady state is reached in about 9 ms.
- Step response for angle = 15 deg and velocity = 40 km/h: the difference in angle between the front wheels is in the order of 3 degrees, while for the rear wheels the difference is negligible. The difference between the front and rear wheels is about 10–12 degrees. The start of rotation of the rear wheels shows a delay of about 2 ms which is justified because of the large angle deviation. A small ringing (much smaller than the 5 deg case) is observed before the steady state. The steady state is reached in about 5 ms.

- Step response for angle = 15 deg and velocity = 75 km/h: the difference in angle between the front wheels is 2 degrees, while in the rear wheels the difference is very small. The difference between the front and rear wheels is about 10–12 degrees. The start of the rotation of the rear wheels shows a delay of about 2 ms which is justified because of the large difference in angle. A small ringing (much smaller than the 5 deg case) is observed before the steady state. The steady state is reached in about 4 ms.
- Step response for angle = 25 deg and velocity = 5 km/h: the difference in angle between the front wheels is about 11 degrees, while for the rear wheels the difference is about 6 degrees. The difference between the front and rear wheels is approximately 9–10 degrees. The start of rotation of the rear wheels shows a delay of about 2 ms which is justified because of the large angle deviation. A subtle ringing is observed before the steady state. The steady state is reached in about 13 ms.
- Step response for angle = 25 deg and velocity = 25 km/h: the difference in wheel angles has a constant deviation of about 5 to 6 degrees from wheel to wheel, while the onset of rotation shows a lag of about 1 to 2 ms from wheel to wheel. A subtle ringing is observed before the steady state. The steady state is reached in about 9 ms.
- Step response for angle = 25 deg and velocity = 50 km/h: the difference in angle between the front wheels is about 8 degrees, while for the rear wheels the difference is very small. The difference between the front and rear wheels is approximately 22 degrees. The start of rotation of the rear wheels shows a delay of about 6 ms which is justified because of the large angle deviation. A subtle oscillation is observed before the steady state. The steady state is reached in about 8 ms.
- Step response for angle = 35 deg and velocity = 5 km/h: the difference in angle between the front wheels is about 11 degrees, while for the rear wheels the difference is about 7 degrees. The difference between the front and rear wheels is approximately 35 degrees. The start of rotation of the rear wheels shows a delay of about 6 ms which is justified because of the large angle deviation. No ringing is observed before the steady state. The steady state is reached in about 18 ms.
- Step response for angle = 35 deg and velocity = 15 km/h: the difference in angle between the front and rear wheels is about 3 degrees. The difference between the front and rear wheels is approximately about 30 degrees. The start of rotation of the rear wheels shows a delay of about 5 ms which is justified because of the large angle deviation. No ringing is observed before the steady state. The steady state is reached in about 16 ms.
- Step response for angle = 35 deg and velocity = 25 km/h: the difference in angle between the front wheels is about 8 degrees, while for the rear wheels the difference is about 6 degrees. The difference between the front and rear wheels is approximately 22 degrees. The start of rotation of the rear wheels shows a delay of about 3 ms which is justified because of the large angle deviation. No ringing is observed before the steady state. The steady state is reached in about 13 ms.

In Figure 13 a more challenging scenario is presented, where the control system is tested under heavy load conditions. By keeping the input angle and speed constant (25 degrees and 25 km/h) while increasing the load on each single wheel (specifically tripled, thus 0.3 Nm), the performance of the control system when a wheel is facing different loads can be evaluated. This analysis provides a better understanding of the robustness of the control system and its ability to maintain the desired wheel angles despite external disturbances.

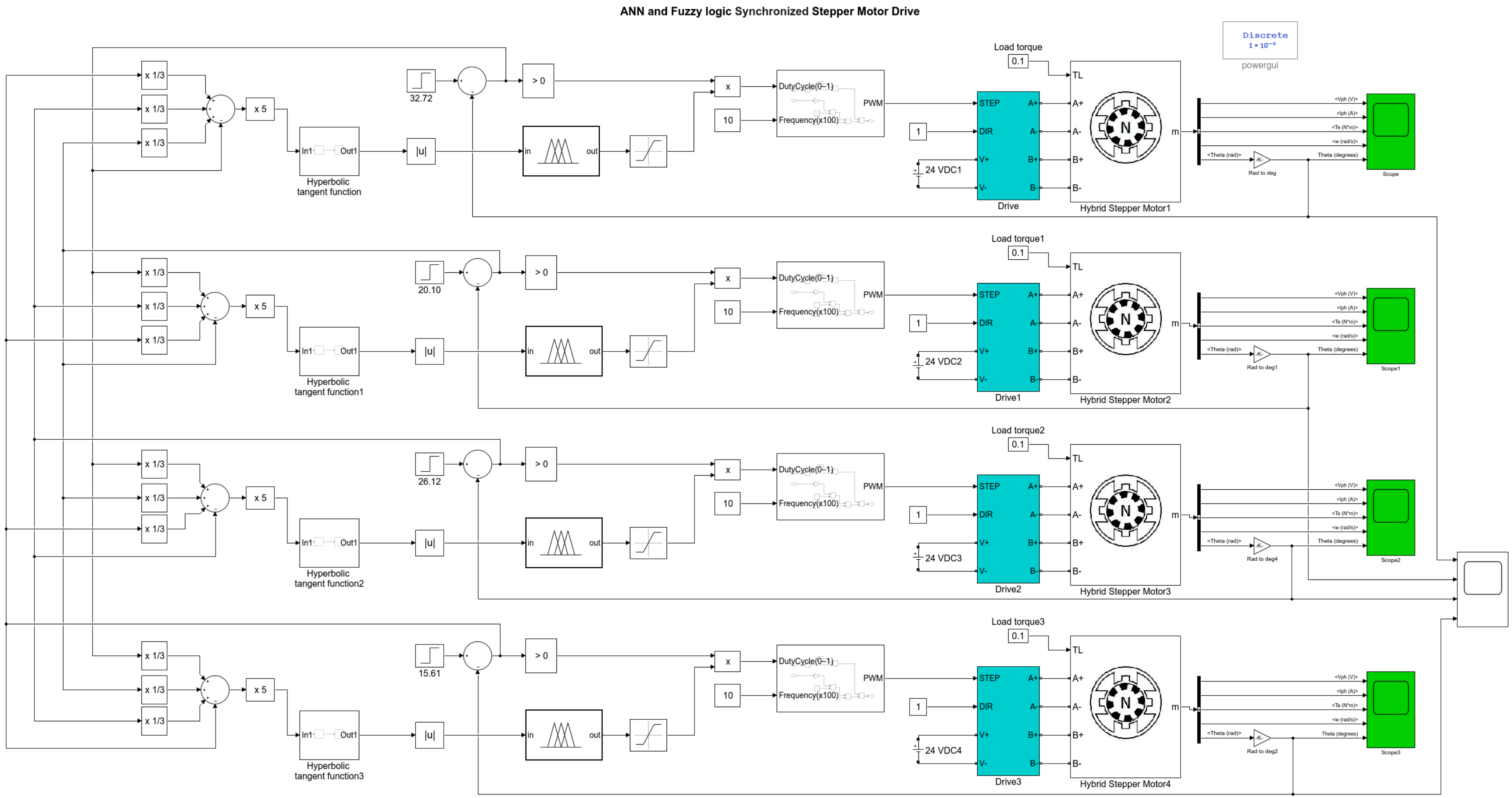


Figure 10. Block diagram of the proposed four stepper motor steering scheme in Matlab/Simulink platform.

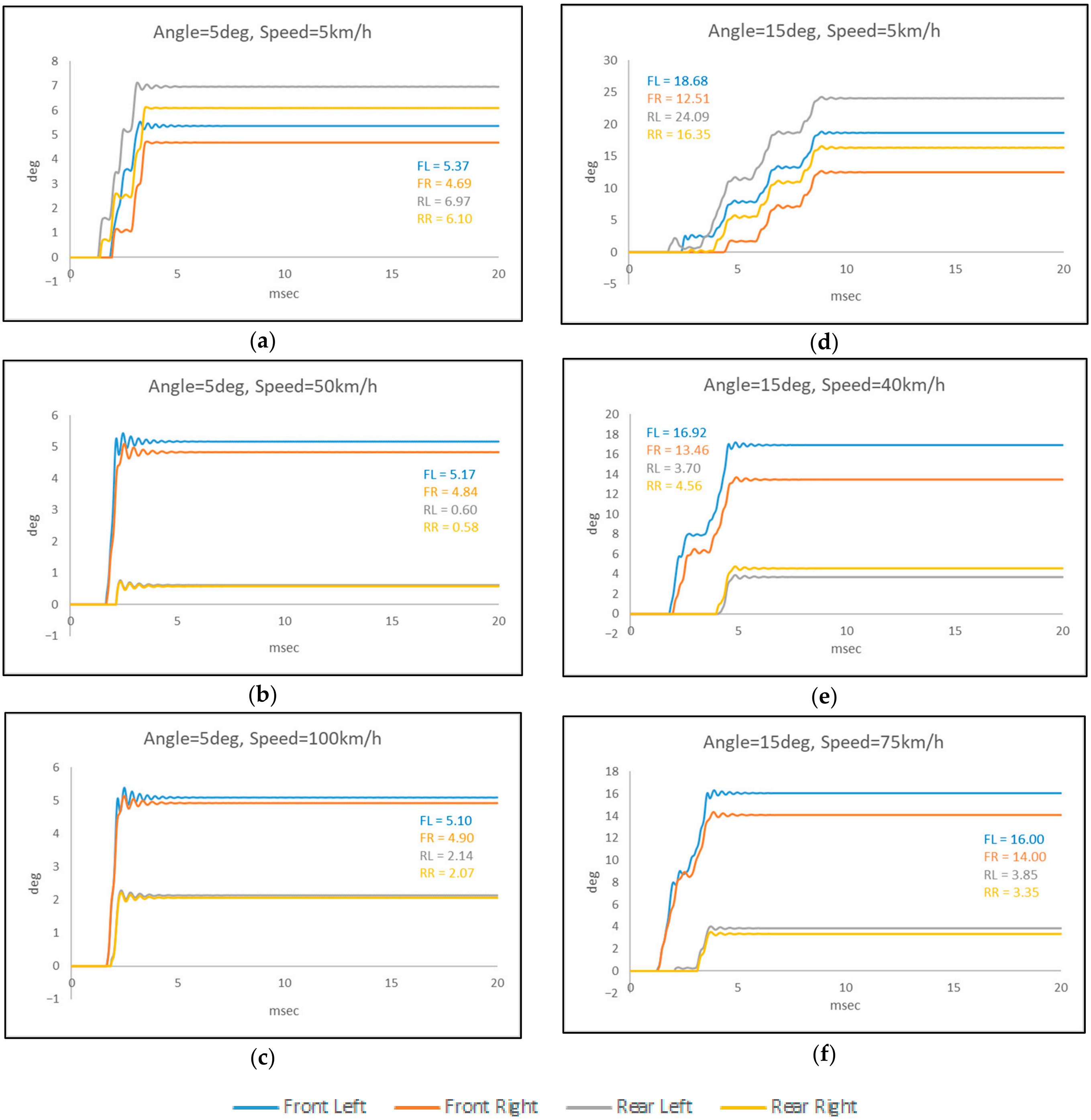


Figure 11. (**a**) Step response at 5 deg and 5 km/h; (**b**) Step response at 5 deg and 50 km/h; (**c**) Step response at 5 deg and 100 km/h; (**d**) Step response at 15 deg and 5 km/h; (**e**) Step response at 15 deg and 40 km/h; (**f**) Step response at 15 deg and 75 km/h.

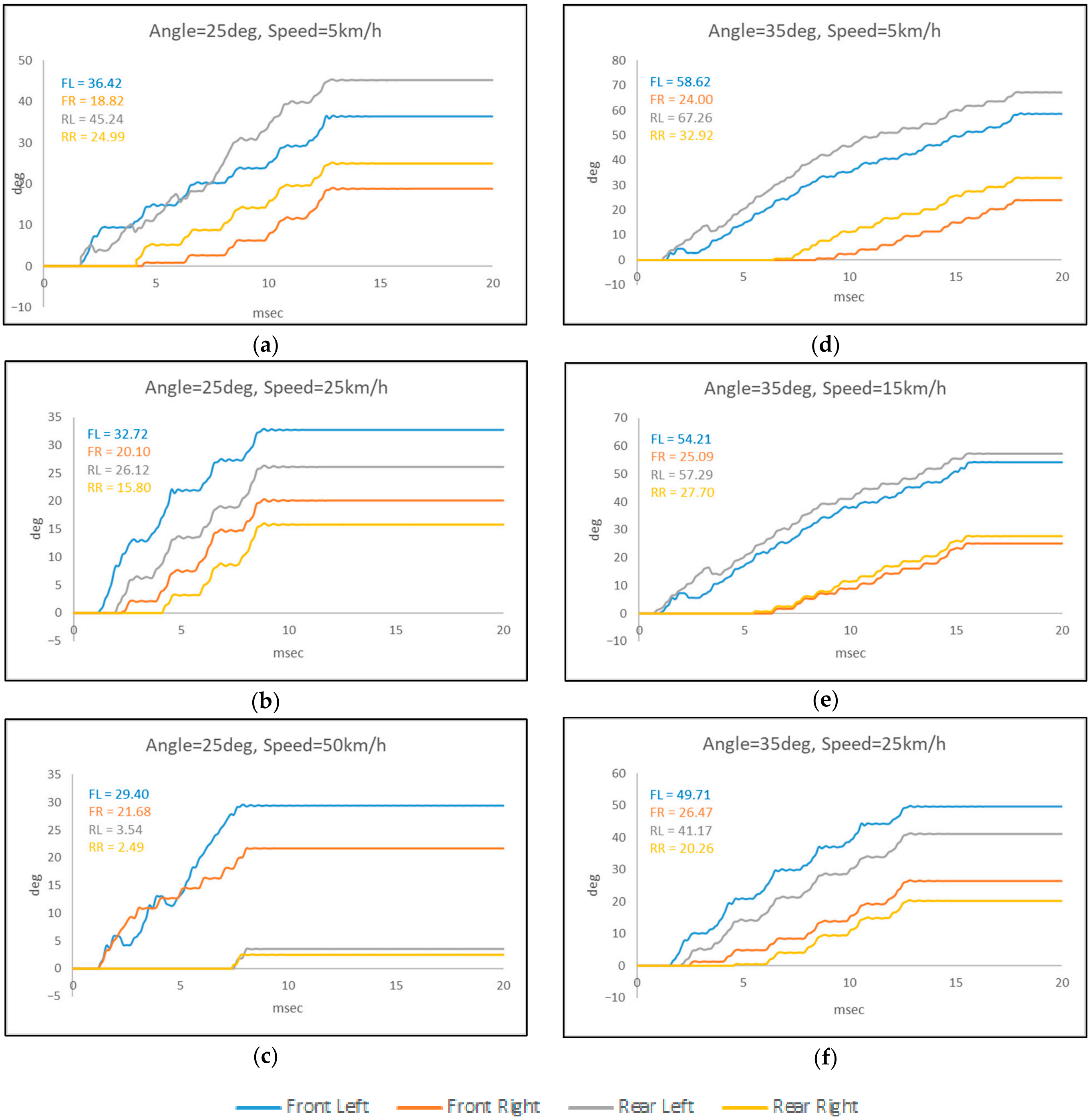


Figure 12. (**a**) Step response at 25 deg and 5 km/h; (**b**) Step response at 25 deg and 25 km/h; (**c**) Step response at 25 deg and 50 km/h; (**d**) Step response at 35 deg and 5 km/h; (**e**) Step response at 35 deg and 15 km/h; (**f**) Step response at 35 deg and 25 km/h.

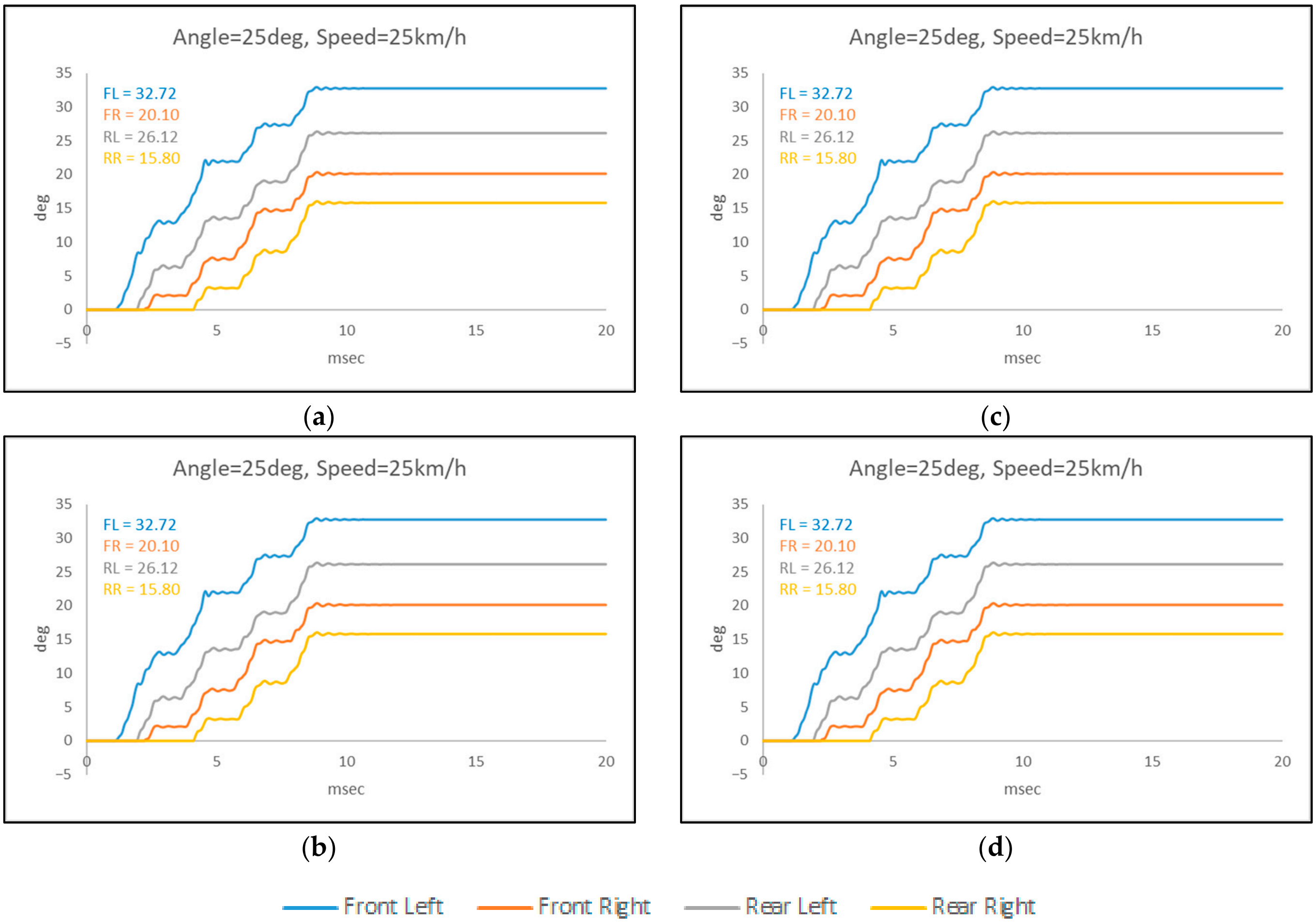


Figure 13. (**a**) Step response at 25 deg and 25 km/h—front left motor overloaded ×3 (0.3 Nm); (**b**) Step response at 25 deg and 25 km/h—rear left motor overloaded x3 (0.3 Nm); (**c**) Step response at 25 deg and 25 km/h—front right motor overloaded ×3 (0.3 Nm); (**d**) Step response at 25 deg and 25 km/h—rear right motor overloaded ×3 (0.3 Nm).

General observations from the simulation results:

- The shorter the rotation, which is more prominently observed in responses below 5 ms, the greater the ringing before reaching a steady state. In longer response times, this phenomenon is eliminated, and the system smoothly reaches a steady state.
- The greater the difference in the angles between the wheels, the slower the onset of the response in the wheels that have the smallest angle to turn.
- The larger the angle a wheel needs to turn, the more time it requires. The longest response is observed in the combination of angle = 35 deg and velocity = 5 km/h, taking 18 ms, while the shortest is in the combination of angle = 5 deg and velocity = 100 km/h, taking 2 ms.
- For the same angle of rotation, the higher the speed of the vehicle, the sooner the steady state is reached.
- In all combinations of angle and velocity, all wheels, regardless of their load, reach a steady state simultaneously.

Overall, this work aims to provide a comprehensive evaluation of the proposed control method. By simulating various scenarios and assessing the control response, insights can be gained into the system's behavior, its ability to achieve simultaneous wheel angles, and its robustness under different operating conditions. These findings can potentially contribute to the development of more effective control strategies for multi-wheel systems.

6. Conclusions

This paper presents a real-time robust controller for 4WIS systems in EVs. The main achievement of this work is the successful integration of neural networks and fuzzy logic within a decentralized control approach. This groundbreaking approach offers several key advantages:

✓ Stability: The proposed control scheme ensures high precision and accuracy in steering control, guaranteeing a level of stability that surpasses existing systems.

✓ Efficiency: It optimizes energy consumption, leading to a notable increase in the overall efficiency of 4WIS systems in EVs.

✓ Practicality: Beyond theoretical applications, this method is designed with practicality in mind, opening doors for real-world implementation in electric vehicles.

Simulation results form a strong foundation for this research, showcasing the remarkable synchronization capability of stepper motor rotations. These results hold even in the face of various input variations and load conditions, setting this system apart from its predecessors.

Extensive simulation tests have been conducted to evaluate the robustness and synchronization capabilities of the proposed controller. These tests were introduced with representative steering angles and vehicle velocities, all of which successfully reinforce the system's resilience. Based on the results of the simulation process, the following extrapolations are obtained:

➢ The application of neural networks greatly simplifies the computational power of the fuzzy logic controller.

➢ The controller of each wheel is able to monitor the position of the other wheels, thus providing the vehicle with safety against derailment.

➢ Finally, the proposed control system achieves the required response of the vehicle angle to the wheels even in the case of uneven and abrupt load changes.

The next critical step is the validation of these findings through experimental tests. Implementing the proposed control scheme in a physical system will enable researchers to assess its performance under real-world conditions. These experiments will provide the empirical evidence necessary to support the viability and effectiveness of the developed controller.

To sum up, this research emphasizes the potential of the proposed control scheme to significantly enhance the efficiency of 4WIS systems in electric vehicles. The combination of neural networks, fuzzy logic, and decentralization offers notable advantages in terms of stability, efficiency, and practicality. While the simulation results provide a solid foundation, forthcoming experimental tests will further confirm the controller's capabilities in real-world scenarios.

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