Speed Control of An Autonomous Electric Vehicle Using Fuzzy Logic With Computer Vision-Based Input

Regita Fortuna Sinulingga, Bhakti Yudho Suprapto, Dimsyiar M Al Hafiz, Farhan Abie Ardandy, Javen Jonathan, Suci Dwijayanti

Department of Electrical Engineering, Faculty of Engineering, Sriwijaya University, Palembang, 30662, Indonesia

ARTICLE INFORMATION

ABSTRACT

A robust speed control mechanism ensures safety in an autonomous electric vehicle system. Such a system must dynamically adjust the vehicle's speed based on its surrounding environment. This research employs computer vision for object and road detection to measure the distance between the car and nearby objects. Fuzzy logic methods—specifically Mamdani and Sugeno—are utilized to automatically and stably regulate the speed of autonomous electric vehicles from their starting point to their destination. The control system considers various road conditions, including left-slanting, straight, and right-slanting roads, and the real-time presence or absence of objects. Testing is conducted across three real-world scenarios using distance and steering angle inputs. The servo angle represents the output, which ranges from 0 to 1800 and corresponds to the vehicle's speed. The results indicate that the Mamdani method provides greater speed control accuracy than the Sugeno method, which relies on a singleton output. For conditions involving left-slanting, straight, and right-slanting roads with objects within a 10-meter range, the Mamdani method produced outputs of 1370, 1800, and 1370, respectively, aligning well with predefined speed control rules. In contrast, the Sugeno method yielded 880, 1470, and 650 outputs for the same conditions, which did not adhere to the predefined rules for slow, medium, and fast speeds. In conclusion, the Mamdani method demonstrates superior accuracy and suitability for speed control in autonomous electric vehicles compared to the Sugeno method.

INTRODUCTION

An autonomous electric vehicle is a self-driving vehicle powered by electricity. These vehicles can make decisions such as moving, stopping, turning right or left. Autonomous cars are specifically designed to follow desired paths, and their powertrain can provide high power, smooth operation, and fast dynamic response compared to vehicles using internal combustion engines [1]. As a result, autonomous electric vehicles play a crucial role in modern intelligent transportation systems. In autonomous vehicle control, some modules include environment perceptions and positioning, decision planning, and execution control [2].

The advantages of autonomous electric vehicles include their environmentally friendly nature, as they do not produce pollution or emissions. Additionally, they can improve road utilization and vehicle safety and reduce mobility costs [3], and they have the potential to reduce accidents and energy consumption [4]. Autonomous electric vehicles require lateral and longitudinal controllers to perform all these functions. The lateral controller adjusts the steering angle of the wheel, while the longitudinal manages the speed [5]. Thus, a speed control system is necessary to ensure that safety objectives are met and driving comfort is maintained [6].

Speed is a crucial factor in the operation of autonomous electric vehicles because these vehicles must be able to adapt their speed to the surrounding environment. Therefore, speed control in autonomous vehicles remains a key topic in their development.

In previous research, a remote control-based speed control system was designed. The speed of electric vehicles was controlled remotely using a remote control [7]. Meanwhile, [8] used an adaptive Proportional Integral Derivative (PID) method to control the nonlinear longitudinal dynamics. Then, [9] employed PID control for the DC motor of an electric vehicle. [10] proposed a fractional PI controller for low-speed longitudinal control. Furthermore, [11] utilized the Internet of Things (IoT) as the uncrewed ground vehicle (UGV) control system. Meanwhile, [12] proposed combining reinforcement learning with PID to control the track trajectory of the mobile robot. [13] also used PID for speed control with the metaheuristics of genetic algorithms, memetic algorithms, and mesh adaptive direct search to optimize the parameter values of the PID controller.

Besides PID, another approach to controlling the speed of autonomous vehicles is to utilize computer vision, which is widely used by autonomous vehicles for object recognition, such

as lanes and obstacles on the road. [14] used computer vision in a self-driving car with machine learning. This research used a four-wheeled robot to move automatically based on object detection, recognizing objects such as traffic signs and lanes. Another study used a deep neural network to learn the scenes and drivers' behavior in vehicle controllers [15][16].

Another approach to speed control was undertaken by [17]. In this study, the PID controller was used to maintain the optimal speed, and the lateral control was designed using both feedforward and feedback controllers. [18] utilized backpropagation in conjunction with PID for lateral control, where the backpropagation was employed to determine the parameters of PID. Meanwhile, [19] proposed the use of fuzzy logic-based lane detection. In other studies, model predictive control (MPC) is used together with PID for speed control [20][21].

In previous research, speed control for autonomous vehicles was implemented only on roads with separators and was often in the form of a simulation [8][9]. However, roads in Indonesia generally do not have separators. Additionally, speed control systems only considered the road without taking into account objects that the vehicle may encounter [8], and they used PID controllers [7]. A new PID self-tuning fuzzy controller was proposed to control the speed response of autonomous vehicles. By adding fuzzy logic control to the conventional PID method, the controller could adjust the PID to improve the stability and accuracy of the speed control system. Simulation experiments demonstrated that the proposed method could reduce system overshoot and enhance the system's anti-interference ability with a certain level of robustness [22]. To address these issues, this research developed a speed control system for autonomous vehicles using fuzzy logic with inputs from objects and road detection. Fuzzy logic has shown good performance in previous research [19]. In addition, the rules in fuzzy logic may replicate human driving, which is essential for mimicking speed control in autonomous vehicles. Furthermore, the roads traveled by autonomous vehicles in this research did not have separators, representing real-world conditions in Indonesia. The object and road detection results obtained through computer vision were used to measure the distance between the vehicle and objects, enabling the autonomous vehicle to make precise decisions regarding whether to move fast, moderate or slow based on the road conditions it encountered. Consequently, the autonomous vehicle could adjust its speed according to the environmental conditions it encountered. Thus, this study aims to implement a speed control system using fuzzy logic, utilizing input from the detected object's position and steering angle obtained through computer vision-based object and road detection. Additionally, the research assesses the real-time performance of fuzzy logic in speed control.

METHODS

Design Autonomous Electric Vehicle

In this phase, the design planning for the autonomous electric vehicle is carried out. The design specifies device types, placement, and hardware layout. The positions of the hardware are depicted in Figure 1.
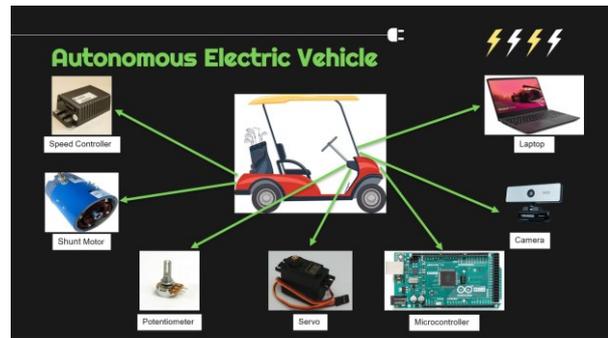

Figure 1. Design of the autonomous electric vehicle

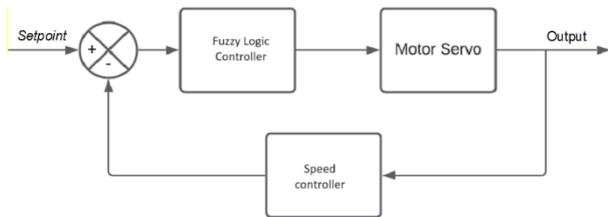Figure 2 shows the block diagram of the speed controller using fuzzy.

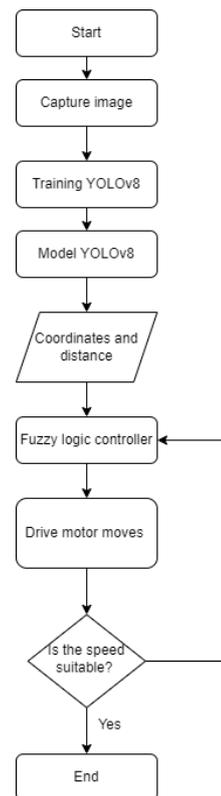Figure 2. Block Diagram of Speed Controller

System Design

Figure 3. Flowchart System

The flowchart of the system can be seen in Figure 3. It begins with image capture. Next, the image is processed using YOLOv8 computer vision to determine coordinates and distances. These outputs from YOLO are then used to control speed in the fuzzy logic system. This research uses a fuzzy logic system for speed control, with inputs obtained from distance readings through computer vision based on deep learning [23]. The input
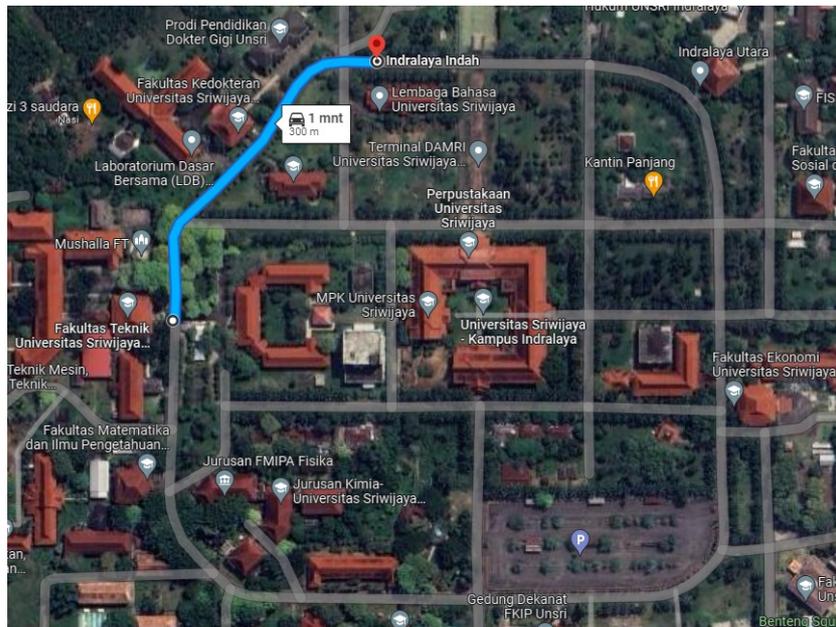
Figure 4. Testing Route

membership functions consist of distance from the object's position, with three members, and steering angle, with three members. These three-member membership functions are employed for real-time testing.

Table 1 shows the input values for distance, and Table 2 shows the input values for steering angle, using the 3-member membership function. The output, which is the servo angle, can be found in Table 3. This output controls the speed of the autonomous vehicle's speed control system.

Table 1. Input Distance Three Members

Distance (meter)	Variable
1 – 5	Close
3 – 8	Medium
6 – 10	Far

Membership functions for the input distance consist of the following variables: "Close" with a range of 1 - 5 meters, "Medium" with a range of 3 - 8 meters, and "Far" with a range of 6 - 10 meters. These ranges are considered within the proximity of the distance between the autonomous vehicle and the object, as the object detection system can detect objects up to 10 meters away. Meanwhile, membership functions for the input steering angle include the following variables: "Right Slanting" with a range of 0 - 40^0, "Straight" with a range of 20 - 70^0, and "Left Slanting" with a range of 50 - 90^0. For the output, with 3-member functions, the variables are as follows: "Slow" with a range of 0 - 80^0 for the Mamdani method and a value of 60^0 for the Sugeno method, "Medium" with a range of 40 - 140^0 for the Mamdani method and a value of 120^0 for the Sugeno method, and "Fast" with a range of 100 - 180^0 for the Mamdani method and a value of 180^0 for the Sugeno method.

Table 2 represents the fuzzy input variable Steering Angle, which categorizes the direction the autonomous vehicle turns. This variable is divided into three overlapping fuzzy sets to allow smooth transitions between directional states. The Left Slanting category covers angles from 0 to 40 degrees, indicating a leftward

turn. The Straight category spans from 20 to 70 degrees, representing when the steering is relatively centered. Meanwhile, the Right Slanting category covers 50 to 90 degrees, indicating a rightward turn. These overlapping ranges help the fuzzy logic controller interpret gradual changes in the steering direction, ensuring more precise vehicle control during navigation.

Table 2. Input Steering Angle Three Members

Steering Angle (^{0})	Variable
0 – 40	Left slanting
20 – 70	Straight
50 – 90	Right slanting

Table 3 defines the system's output, which is the Servo Angle responsible for controlling the vehicle's speed. The output uses three membership categories: Slow, Medium, and Fast. For the Mamdani method, each output category is represented by a range: 0–80 for Slow, 40–140 for Medium, and 100–180 for Fast, providing a fuzzy range of values. In contrast, the Sugeno method simplifies the output to a single fixed value for each category: 60 for Slow, 120 for Medium, and 180 for Fast. This structure allows the Mamdani method to offer more flexible, gradual control, while the Sugeno method provides faster computation and is more suitable for real-time control systems.

Table 3. Output Servo 3 Members

Mamdani	Sugeno	Variable
0 – 80	60	Slow
40 – 140	120	Medium
100 – 180	180	Fast

The route taken during the testing is located at Sriwijaya University Indralaya Campus. The testing route is taken from the starting point at the Faculty of Engineering to the finishing point at the Faculty of Medicine, as shown in Figure 4.

RESULTS AND DISCUSSION

Results of Equipment Design

The design of the autonomous electric vehicle compromises both the mechanical design and the design of the wiring components. The components utilized in this design include the Servo Tower Pro MG995, a 10k potentiometer, a Curtis 1266 Speed Controller, and a shunt motor controlled by an Arduino Mega microcontroller. Figure 5 illustrates the results of this equipment design.

Figure 5. Autonomous electric vehicles

The input variable for distance for the 3 members consists of close, medium, and far, as seen in Figure 6.
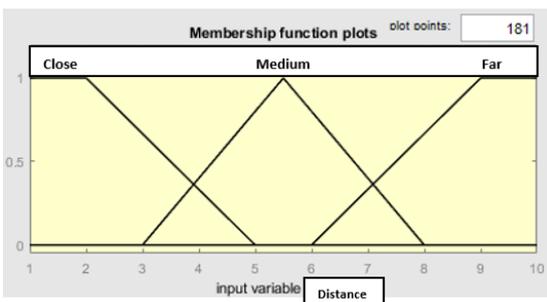

Figure 6. Membership Function Input Distance

Figure 6 represents the shoulder and triangular curves for the input distance variable for the three members. The steering angle input for the three members includes left slanting, straight, and right slanting, which can be seen in Figure 7.
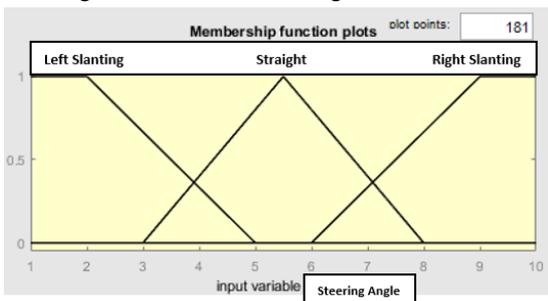

Figure 7. Membership Function Input Steering Angle

In this phase, fuzzy rules are determined as a reference to obtain motor movement output. This research uses two input variables, each with three members, for real-time testing, so the rules for the three members can be seen in Table 4. These fuzzy rules are determined based on the membership functions specified in Tables 1, 2, and 3. Three conditions of the input distance and three

conditions of the input steering angle result in 9 rules, starting from rule 1 to rule 9.

Table 4. Fuzzy Rules 3 Members

Rules Number	Input		Output
	Steering Angle	Distance	Speed
1	Left Slanting	Close	Slow
2	Left Slanting	Medium	Slow
3	Left Slanting	Far	Medium
4	Straight	Close	Slow
5	Straight	Medium	Medium
6	Straight	Far	Fast
7	Right Slanting	Close	Slow
8	Right Slanting	Medium	Slow
9	Right Slanting	Far	Medium

The Results of Real-time Testing

The conducted experiments and their results are presented in graphs, which can be observed in Figures 8, 9, 10, and 11.
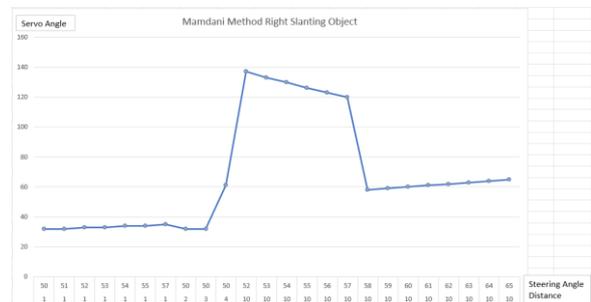

Figure 8. Right slanting, object detected using the Mamdani method

Figure 8 is a graph of speed output using the Mamdani method when there is an object where the object is at 1-10 meters. This distance is calculated based on the object detection results using a camera. Meanwhile, the steering condition is in the range of 50 - 65^0. The steering angle is also obtained from calculations based on object detection. This steering angle condition is for a right slant because it matches the route from the Faculty of Engineering to the Faculty of Medicine. In the first data set, you can see that the input distance value is 1 meter, which means it's close, and the input angle value is 50^0, which means it's a right slant. The output value of the servo angle is 32^0, which means it's slow. The results are by the predefined rules.

The graph shows that all distance and steering angle conditions align with the established rules. In the last data set, when the car's distance from the object is 10 meters, which means it's far, and the steering angle is 65^0, the servo angle is 65^0, indicating a moderate speed.

The results from the Mamdani method show that fuzzy logic can be used as a speed controller for autonomous vehicles.

Figure 9. Right slanting, the object detected using the Sugeno method

Next, testing was conducted under the same conditions as before, with an obstructing object for the autonomous vehicle and a right-slant road using the Sugeno method. The results of this testing can be seen in Figure 9. In the first set of data, you can see that the input distance value is 1 meter, which means it's close, and the input angle value is 62^0, which means it's a right slant. The output value of the servo angle is 60^0, indicating a slow speed. The results are by the predefined rules.

The Mamdani and Sugeno methods can determine output matching distance and steering angle input conditions. However, the Mamdani output is more precise than that of Sugeno because the Sugeno method provides a single output value. This results in situations where, for example, at 10 meters and a steering angle of 66^0, the Sugeno output is 137^0. In contrast, in the Mamdani method, with the same distance condition and a steering angle of 65^0, the output is 65^0.
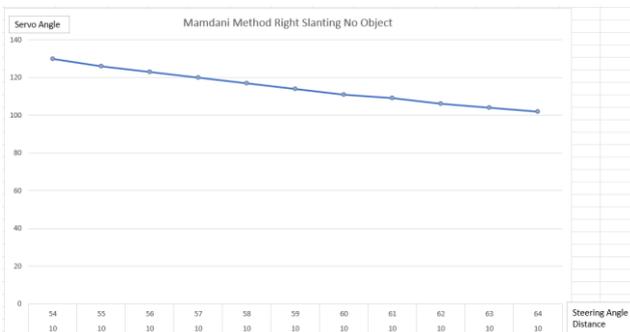

Figure 10. Right slanting, no object detected using the Mamdani method

Figure 10 displays a graph of speed output using the Mamdani method when no object is detected at 10 meters. This distance is calculated based on camera-based object detection results, and the steering angles fall within the range of $54 - 64^0$, indicating a "right slanting" condition along the route from the Faculty of Engineering to the Faculty of Medicine.

In the first data point, the input distance is 10 meters ("close"), and the input steering angle is 54^0 ("right slanting"). The output servo angle is 130^0 ("medium"), aligning with the predefined rules. The graph illustrates that all distance and steering angle conditions adhere to the established rules.

In the last data, with 10 meters ("far") and a steering angle of 64^0, the servo angle is 102^0 ("medium"). The results from the

Mamdani method demonstrate the effectiveness of fuzzy logic as a speed controller for autonomous vehicles.
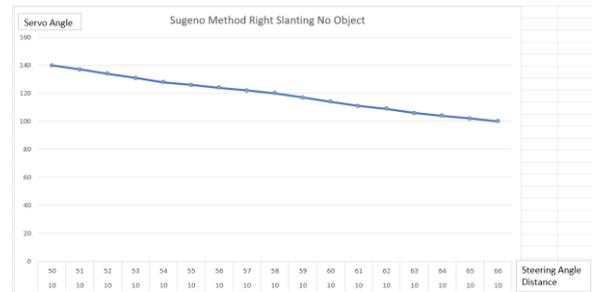

Figure 11. Right slanting, no object detected using the Sugeno method

Next, using the Sugeno method, testing was conducted under the same conditions as before, which involved an obstacle obstructing the autonomous vehicle and a right-slanting road condition. The results of this testing can be seen in Figure 11. The first data point shows that the input distance is 10 meters, indicating "close," and the input steering angle is 50^0, indicating "right slanting." The output servo angle is 140^0 ("medium"), aligning with the predefined rules.

The Mamdani and Sugeno methods produce outputs corresponding to distance and steering angle input conditions. However, the Mamdani method is more precise than Sugeno because the Sugeno method generates a single-value output. For example, at 10 meters and a steering angle 54^0, the Sugeno method produces an output of 128^0, while the Mamdani method yields 130^0 with the same inputs.

The fuzzy logic controller system can effectively control speed using the Sugeno and Mamdani methods from all the testing conducted for various conditions, including straight, left slanting, right slanting, and straight with or without objects. The speed output represented by the servo indicates results that align with the predefined rules. However, the Mamdani method demonstrates more accurate output than Sugeno, which uses only singleton output values.

This study has demonstrated that a fuzzy controller can effectively serve as the speed controller for autonomous vehicles in real time across various scenarios. Unlike previous studies where fuzzy controllers were implemented for speed control in robot cars [24] [25]. This study applied the controller to real-time autonomous vehicle settings.

CONCLUSIONS

Testing results indicate that both Mamdani and Sugeno fuzzy logic methods effectively control the speed of autonomous electric vehicles from their starting locations to destinations, utilizing inputs such as distance and steering angle through three membership functions. Real-time tests involved distance readings from camera sensors (1 to 10 meters) and steering angles (0 to 90 degrees), addressing various road conditions (left slants, straight paths, right slants) and the presence of obstacles. The Mamdani method consistently yielded more accurate speed outputs compared to the Sugeno method, which only provides singleton

outputs; for left slants, straight paths, and right slants with an object at 10 meters, the Mamdani outputs were 137º, 180º, and 137º, respectively, aligning with predefined speed control rules. In contrast, the Sugeno method produced outputs of 88º, 147º, and 65º, failing to meet designated classifications of slow, medium, or fast. Consequently, the Mamdani method demonstrates superior accuracy, with outputs ranging from 0º to 180º. Future work will involve implementing type-2 fuzzy logic for comparative analysis against type-1 fuzzy logic in speed control applications for autonomous vehicles.

ACKNOWLEDGMENT

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AUTHORS BIOGRAPHY

Regita Fortuna Sinulingga
was born in Batam on May 1, 2001. She completed her undergraduate studies in the Electrical Engineering department at Universitas Sriwijaya. Her research interests are related to fuzzy logic and control systems

Bhakti Yudho Suprapto
was born in Palembang, South Sumatra, Indonesia, in February 1975. He is an Academic Staff Member of the Department of Electrical Engineering at Universitas Sriwijaya. He completed his master's and doctoral programs in electrical engineering at Universitas Indonesia (UI). His research interests include control and intelligent systems.

Dimsyiar M Al Hafiz
was born in Palembang on Octovber 1, 2002. He completed his undergraduate studies in the Electrical Engineering department at Universitas Sriwijaya. His research interests are related to control systems, Robotic, and intelligent systems.

Farhan Abie Ardandy
was born in Tanjung Enim on July 14, 2001. He completed his undergraduate studies in the Electrical Engineering department at Universitas Sriwijaya. His research interests are related to control systems and image processing.

Javen Jonathan
was born in Palembang on Octovber 1, 2001. He completed his undergraduate studies in the Electrical Engineering department at Universitas Sriwijaya. His research interests are related to control systems and robotics.

Suci Dwijayanti
Received the M.S. degree in electrical and computer engineering from Oklahoma State University, Stillwater, OK, USA, in 2013, and the Ph.D. degree from the Graduate School of Natural Science and Technology, Kanazawa University, Japan, in 2018. From 2007 to 2008, she was an Engineer with ConocoPhillips Indonesia Inc., Ltd. Since 2008, she has been with the Department of Electrical Engineering, Universitas Sriwijaya, Indonesia. Her research interests include signal processing and machine learning.