Simulation of a Differential Drive Mobile Robot with Fuzzy Logic Control

Rendyansyah[1] and Hera Hikmarika[2]
[1,2]Departement of Electrical Engineering, Faculty of Engineering, University of Sriwijaya
Palembang, Indonesia
correponding author(s): rendyansyah.unsri@gmail.com

Abstrak—Simulasi mobile robot berpenggerak differential dengan penerapan kendali logika fuzzy adalah topik yang menarik dalam bidang robotika. Dalam konteks ini, mobile robot dengan mekanisme penggerak differential memiliki keunggulan dalam manuverabilitas dan ketahanan terhadap area yang sulit. Penerapan sistem kendali logika fuzzy memberikan fleksibilitas dalam menyesuaikan perilaku robot dengan lingkungan sekitarnya, membuatnya mampu beradaptasi dengan kondisi yang berubah-ubah. Dalam simulasi ini, berbagai variabel seperti kecepatan putar roda dan orientasi robot dapat diatur melalui aturan-aturan fuzzy yang dikembangkan. Dalam penelitian ini, simulasi robot telah dilakukan, dan robot dapat menuju target dengan baik dengan pergerakan yang halus. Selain itu, sistem kendali logika fuzzy juga mampu memperhitungkan faktor-faktor tidak pasti dan ambiguitas dalam lingkungan sekitar, sehingga meningkatkan kecerdasan robot dalam mengambil keputusan.

Kata Kunci—*Differential Steering, Fuzzy Logic Control, Mobile robot, Modeling and Simulation*

***Abstract*— Simulation of differentially driven mobile robots using fuzzy logic control is an exciting topic in robotics. In this context, mobile robots with differential drive mechanisms have advantages in maneuverability and resistance to rugged areas. Applying a fuzzy logic control system provides flexibility in adapting the robot's behavior to its surrounding environment, allowing it to adapt to changing conditions. In this simulation, various variables, such as wheel rotation speed and robot orientation, can be regulated through the developed fuzzy rules. In this research, a robot simulation has been carried out, and the robot can reach the target well with smooth movements. The fuzzy logic control system can also consider uncertain factors and ambiguity in the surrounding environment, thereby increasing the robot's intelligence in decision-making.**

Keywords— Differential Steering, Fuzzy Logic Control, Mobile robot, Modeling and Simulation

I. INTRODUCTION

Technological development in the world of robotics is increasingly advanced, and there is a need for increasingly complex control systems. One type of robot that is currently widely used is a mobile robot with a differential drive, which is a robot that has two wheels with rotational speeds that are independent of each other [1]. The control system used in this mobile robot is also increasingly developing, one of which is a fuzzy logic control system [2]. Differentially driven mobile robots are often used in various applications, such as in industry, agriculture, and exploring environments that are dangerous to humans. The advantage of this mobile robot is its ability to move agilely and face various conditions in various areas. However, a good control system is needed to make this robot move efficiently and accurately.

One of the techniques used in mobile robot control systems is fuzzy logic. Fuzzy logic is a branch of artificial intelligence that aims to model uncertain or unclear knowledge into a mathematical form that can be used for decision-making [3][4]. By applying a fuzzy logic control system to a mobile robot with a differential drive, the robot can move more smoothly and optimally in various situations. Several backgrounds must be considered when simulating a differentially driven mobile robot using a fuzzy logic control system. One of them is optimizing robot movements in diverse environments. Therefore, the robot's fuzzy logic control system can adjust its speed and direction of movement automatically based on the surrounding environmental conditions. This control system ensures the robot can move efficiently and safely.

Using a fuzzy logic control system can also increase the accuracy and stability of robot movement. With fuzzy logic control, robots can respond quickly to changes in the surrounding environment, such as obstacles or winding roads [5]. This technique allows the robot to move more precisely and reduces the possibility of errors. Apart from that, using a fuzzy logic control system can also increase the flexibility of robots in carrying out specific tasks. By programming appropriate fuzzy logic rules, robots can quickly adapt to various working conditions; for example, in different environments or when there are disturbances in the robot's movement, a fuzzy logic control system will allow the robot to adapt quickly and effectively [6].

By combining mobile robot technology and fuzzy logic control systems, opportunities will open up to develop intelligent robots that are more complex and can carry out more complicated tasks. A deep understanding of these two fields is required to create a mobile robot simulation with a differential drive using a fuzzy logic control system. Robotics and fuzzy logic researchers need to work together to develop innovative and efficient solutions. This way, opportunities will open up for more intelligent mobile robots that can perform various tasks better. In this research, a mobile robot simulation with a differential drive and the application of a fuzzy logic control system are learning mediums for students to understand the concept of robot movement. By utilizing fuzzy logic to control robot movements, robots become more intelligent, more efficient, and able to adapt to their surrounding environment more optimally. This step will bring significant changes to the world of robotics and open up opportunities to develop more sophisticated robotic applications in the future.

II. Literature Review

A. *Mobile robot with differential drive.*

The mobile robot is designed to move and operate in different environments. One type of mobile robot that is often used is a mobile robot with a differential drive. A differentially driven mobile robot is a type of mobile robot that has two wheels that can move independently, which allows the robot to turn quickly and overcome various obstacles. In theory, differentially driven mobile robots can be explained through robot kinematics. Robot kinematics is the study of robot movement in an area, which is influenced by the robot's ability to interact with its surrounding environment. A mobile robot with a differential drive can be modeled as a mechanical system with two wheels as actuators that produce robot movement [7][8]. Figure 1 shows the physical form of a mobile robot with a differential drive.

Figure 1. Mobile robot with differential drive.

In a mobile robot with a differential drive, the robot's movement can be controlled through the rotation speed of the left and right wheels. By adjusting the difference in rotation speed between the left and right wheels, the robot can turn without changing its direction. Mobile robots with differential drive can also perform reverse movements by turning the left and right wheels in opposite directions. Apart from that, the concept of control theory is also essential in differentially driven mobile robots. The control system on differentially driven mobile robots usually uses PID (Proportional, Integral, Derivative) control or Fuzzy Logic to keep the robot on its path and avoid collisions with surrounding obstacles. By using PID control or Fuzzy Logic, the robot can automatically adjust the speed and direction of its movement to achieve the desired goal.

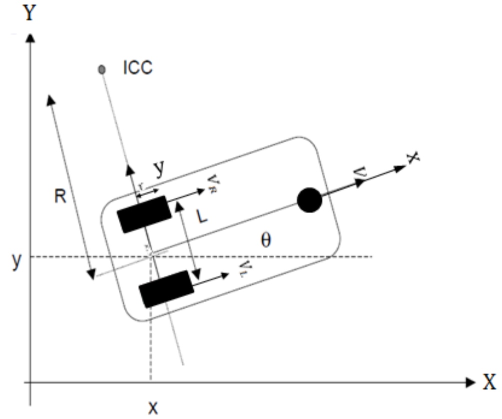


Figure 2. Position and orientation of the mobile robot in a Cartesian coordinate system.

With robot kinematics and control theory, differentially driven mobile robots can be implemented for various applications such as environmental mapping, security patrols, and goods delivery. With its ability to move flexibly and adaptively, mobile robots with differential drive are one of the popular choices in the development of robotic technology today. In conclusion, a differentially driven mobile robot is a type of mobile robot that can move independently with two wheels that can be controlled separately. Based on robot kinematics and control theory, mobile robots with differential drives can carry out various complex tasks in different environments. Through proper development and implementation, differentially driven mobile robots can be an effective solution in various robotic applications in the future. Figure 2 shows the position and orientation of the mobile robot in a Cartesian coordinate system.

Equation (1) expresses the general form of the kinematics equation for a differentially driven mobile robot. It is translated into a nonholonomic transformation form, as in Equation (2).

$$\begin{pmatrix} \dot{x}(t) \\ \dot{y}(t) \\ \dot{\theta}(t) \end{pmatrix} = T_{NH}(q)u(t) \tag{1}$$

$$\begin{aligned}
\dot{q}(t) &= \left(\dot{x}(t), \dot{y}(t), \dot{\theta}(t)\right)^T \\
v(t) &= \frac{1}{2}\left(v_R(t) + v_L(t)\right) \\
\dot{x}(t) &= v(t)\cos\,\theta(t) \\
&= \frac{1}{2}\left(v_R(t) + v_L(t)\right).\cos\,\theta(t) \\
\dot{y}(t) &= v(t)\sin\,\theta(t) \\
&= \frac{1}{2}\left(v_R(t) + v_L(t)\right).\sin\,\theta(t) \\
\dot{\theta}(t) &= \frac{v_R(t) - v_L(t)}{L}
\end{aligned} \tag{2}$$

The next step is to substitute Equation (2) into Equation (1) so that it becomes Equation (3), namely the differential drive mobile robot.

$$\begin{aligned}
\begin{bmatrix} \dot{x}(t) \\ \dot{y}(t) \\ \dot{\theta}(t) \end{bmatrix} &= \begin{bmatrix} \frac{1}{2}\left(v_R(t) + v_L(t)\right)\cos\,\theta(t) \\ \frac{1}{2}\left(v_R(t) + v_L(t)\right)\sin\,\theta(t) \\ \frac{1}{L}\left(v_R(t) - v_L(t)\right) \end{bmatrix} \\
\begin{bmatrix} \dot{x}(t) \\ \dot{y}(t) \\ \dot{\theta}(t) \end{bmatrix} &= \begin{bmatrix} \frac{1}{2}\cos\,\theta(t) & \frac{1}{2}\cos\,\theta(t) \\ \frac{1}{2}\sin\,\theta(t) & \frac{1}{2}\sin\,\theta(t) \\ \frac{1}{L} & -\frac{1}{L} \end{bmatrix} \begin{bmatrix} v_R(t) \\ v_L(t) \end{bmatrix}
\end{aligned} \tag{3}$$

Equation (3) is run by a computer-based program to calculate the values of x, y, and θ using the Runge Kutta algorithm of order 3 [9][10], as in Equation (4).

$$
\begin{aligned}
k_1 &= h\, f\left(x_r, y_r\right) \\
k_2 &= h\, f\left(x_r + \frac{1}{2}h, y_r + \frac{1}{2}k_1\right) \\
k_3 &= h\, f\left(x_r + h, y_r - k_1 + 2k_2\right) \\
y_{r+1} &= y_r + \frac{1}{6}\left(k_1 + 4k_2 + k_3\right)
\end{aligned}
\tag{4}
$$

Runge kutta order 3 is a numerical method for calculating the value of a differential equation without using an integral formulation. This computation is programmed in the computer to obtain the values x, y, and θ. This value measures the robot's distance to the target in Cartesian coordinates.

B. Fuzzy logic.

Fuzzy logic is a branch of artificial helpful intelligence in modeling uncertain or fuzzy systems. Fuzzy logic considers uncertainty and vagueness in human understanding, similar to how humans think. In uncertain environments, fuzzy logic is helpful because it can handle incomplete or inaccurate data. Fuzzy logic control techniques include several essential steps in regulating the behavior of a system. First, fuzzy linguistics determines input and output variables in fuzzy sets. A fuzzy set is a set of values that are not absolute but are on a membership scale between 0 and 1 [3][5].

Second, fuzzy control rules are used to determine the membership level of each activated fuzzy set based on the value of the input variable. These rules are represented in an “if-then” form, where certain conditions are met, and specific actions are performed. The following process is to run fuzzy inference to combine control rules based on the given input variables. This process is carried out by combining the membership levels of each rule based on certain logical operations, such as OR or AND. Third, the defuzzification method converts the fuzzy output back into a crisp value that the system can use. This process involves calculating the center of mass of the activated fuzzy set to produce the final output value [5]. Figure 3 shows the stages of fuzzy logic.

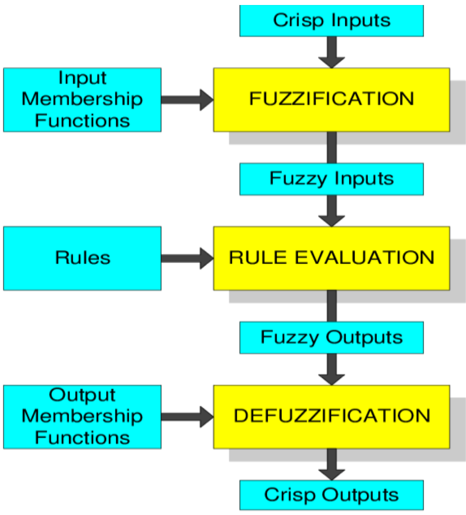


Figure 3. Fuzzy logic stages. [3].

In the context of mobile robots, fuzzy logic can control robot movements based on input from existing sensors. For example, when a robot detects an obstacle in front of it, fuzzy logic can decide to avoid it by changing the direction of the robot's movement. Fuzzy logic can also consider factors such as the speed and direction of the robot's movement based on the surrounding environment. This fuzzy logic technique allows mobile robots to move more adaptively and intelligently in various uncertain situations. In this research, fuzzy logic techniques are applied to control the movement of a differentially driven mobile robot toward a target in Cartesian coordinates.

III. RESEARCH METHOD

In this research, the system is designed as a visual program with a GUI display. The system can be simulated, and the robot's movements can be seen in the simulation. Equations (3) and (4) are programmed in a computer following the rules of the numerical method, namely Runge Kutta order 3. The reason for using the Runge Kutta method order 3 is because this method can solve differential equations for mobile robot systems and display the values of x, y, and θ. The program is made in procedural form so that it can be copied to complete the x, y, and θ values. The x, y, and θ values are the actual position of the robot towards the target. So, the movement of the robot system is regulated using a closed-loop control system based on fuzzy logic. Figure 4 shows a closed-loop control system based on fuzzy logic in a mobile robot system. Based on Figure 4, the fuzzy reasoning gets input from the distance value between the robot and the target and the angle of the robot's facing toward the target. The distance value is obtained by subtracting the set point value from the actual value and using Euclidean distance calculations. The steering angle value towards the target uses trigonometry calculations.

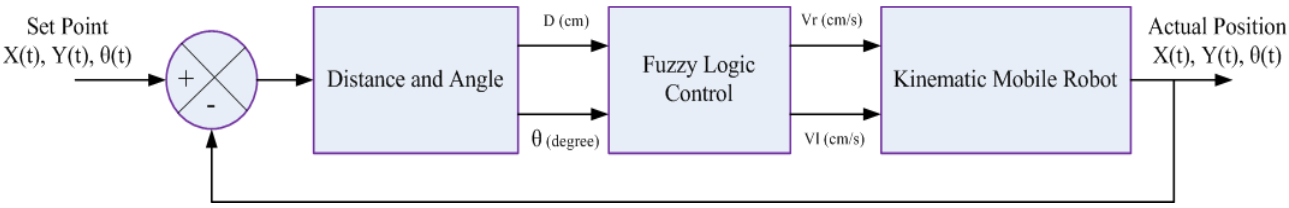
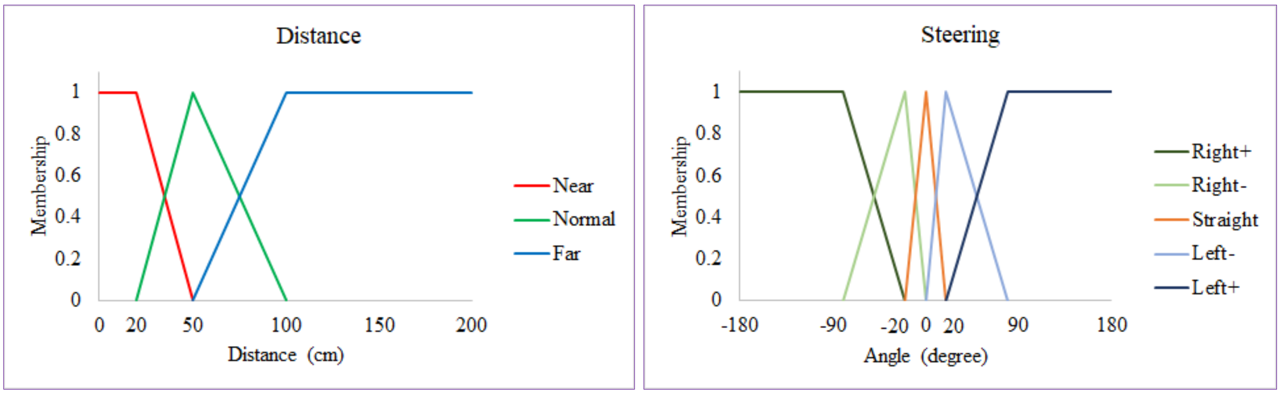
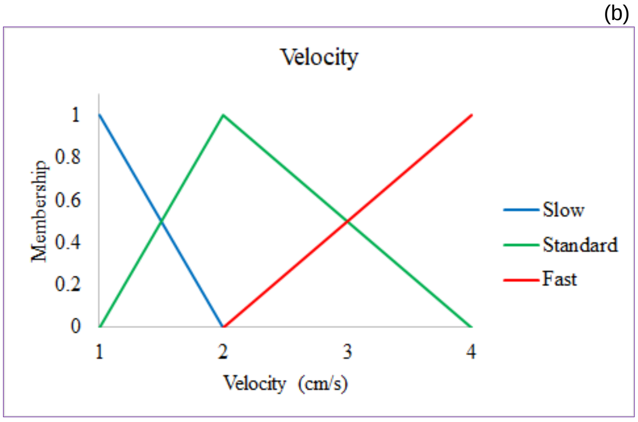


Figure 4. A closed-loop control system is based on fuzzy logic in a mobile robot system.

In this research, fuzzy logic control is formed according to stages, namely fuzzification, inference, and defuzzification. In the fuzzification stage, the process of changing crisp values into fuzzy values is defined, where the distance values are divided into three linguistic variables, namely near, medium, and far. The angle values are formed into five variables, namely left+, left-, straight, right-, and right+. Figures 5.a and 5.b show each degree of membership for fuzzification of distance and steering angle values. The choice of distance value adjusts the diameter of the robot in the simulation, namely 10 cm. For the near category, it is between 20 cm to 50 cm, Normal is 20 cm to 100 cm, and Far is 50 cm to 200 cm.



(a) (b)



(c)

Figure 5. Membership functions for distance, steering angle and speed values, (a) distance, (b) angle, and (c) velocity.

At the inference stage, namely, the process of making decisions based on If-Then logic with a Max-Min mechanism. This stage produces fuzzy output on the output logic of the robot system. The logic formed is 18 rules according to the number of linguistic variables for each input. The linguistic variables for the speed of the robot system are slow, standard, and fast. Figure 5.c shows the membership function for fuzzy output in a robot system. The three linguistic variables of the system output function are filled in the 18 logical rules. Table 1 shows the rule base that was formed to make robot movement decisions. After the inference stage is complete, we proceed to the defuzzification stage, namely changing the fuzzy output value to a crisp value. In this research, the center of average technique is used to obtain the crisp value. A mobile robot with a differential drive has two drives, namely the left and right sides, in this case, the symbols $V_L(t)$ and $V_R(t)$. This value is passed to the mobile robot's kinematics so that it gets the actual position.

Table 1. Rule base for mobile robot movement.

		Distance		
		Near	**Normal**	**Far**
Steering	**Right+**	VL = Fast VR = Slow	VL = Standard VR = Slow	VL = Standard VR = Slow
	Right-	VL = Fast VR = Slow	VL = Fast VR = Standard	VL = Fast VR = Standard
	Straight-	VL = Standard VR = Slow	VL = Standard VR = Slow	VL = Standard VR = Standard
	Straight+	VL = Slow VR = Standard	VL = Slow VR = Standard	VL = Standard VR = Standard
	Left-	VL = Slow VR = Fast	VL = Standard VR = Fast	VL = Standard VR = Fast
	Left+	VL = Slow VR = Fast	VL = Slow VR = Standard	VL = Slow VR = Standard

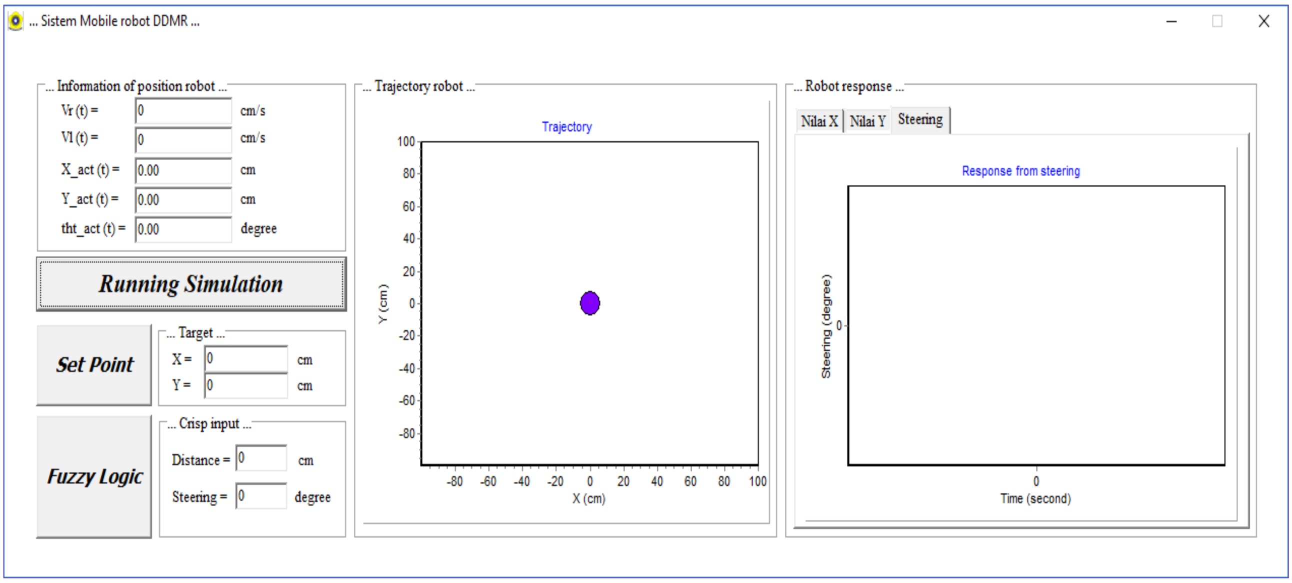


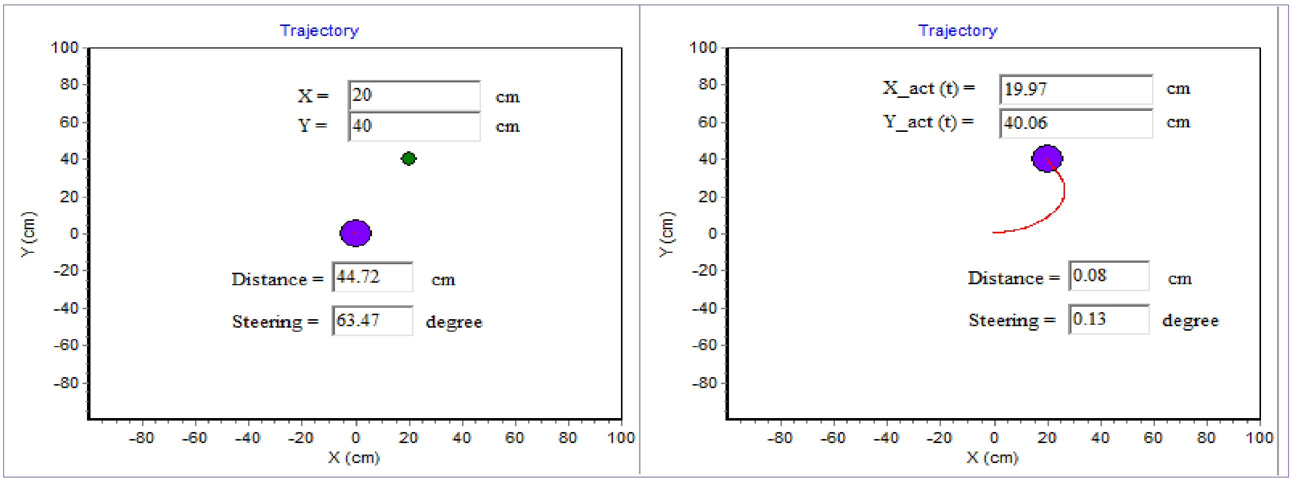
Figure 6. GUI display for mobile robot simulation.

IV. RESULTS AND DISCUSSION

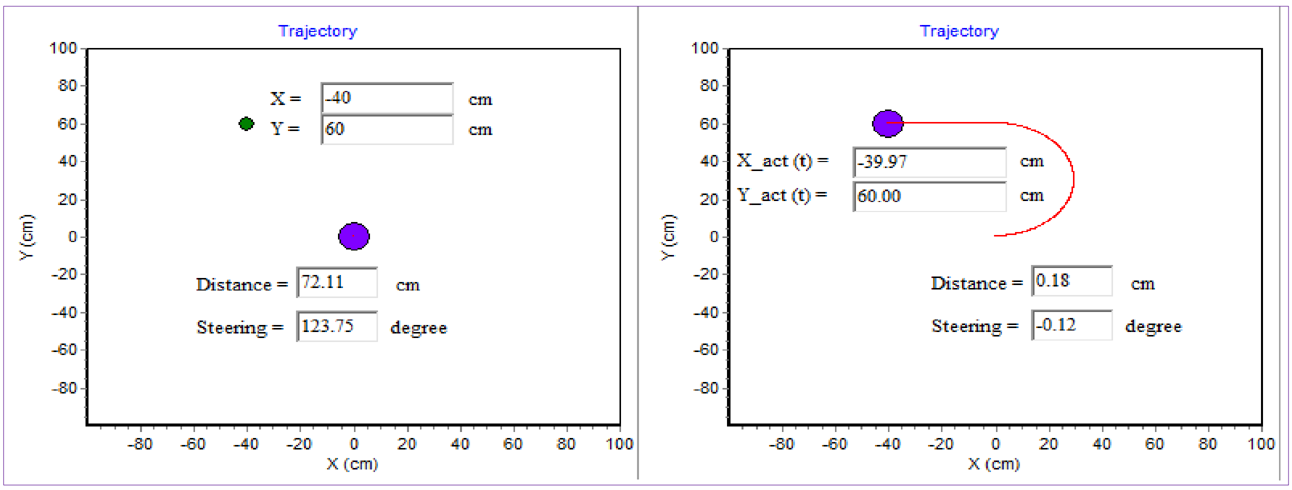
In this research, a mobile robot with a differential drive is run in a visual program simulation in a GUI display. The GUI display is equipped with information about the robot, speed, distance response, steering angle, and trajectory graph, as shown in Figure 6. The robot is in the original position, namely coordinates (0,0), and the actual angle is 0º. The simulation has three buttons, namely "Set-Point," "Running Simulation," and "Fuzzy

Logic Control." This button is a command for running a differential-driven robot system. In the first stage of the experiment, the target was determined in x and y coordinates randomly and was no further than 100 cm. Figure 7.a shows a robot simulation experiment in reaching the target set point (20,40). For the first condition, the set point is x = 20 cm and y = 40 cm, and the robot runs towards that target. In the simulation, the distance between the robot and the target is 44.72 cm, and the steering angle of the robot towards the target is 63.47º. The robot starts to move to the right because the original steering position is 0º towards the x-axis, then the fuzzy logic control regulates the speed of the right wheel to be greater than the left wheel so that the robot turns left towards the target. The robot can reach the target in ± 29 seconds, with the final conditions of distance and steering approaching zero. The following experiment for coordinates in the second quadrant is set to point (-40,60), seen in Figure 7.b. The distance between the robot and the target is 72.11 cm, and the steering angle of the robot towards the target is 123.75º. The robot was initially run to the right because it was in its original position. The robot maneuvered to the left towards the target in ± 77 seconds, and the robot's position stopped at zero distance, and the steering angle was also close to zero.

Experiments for set points (-50,-45), which are in the third quadrant, can be seen in Figure 7.c. The system detected that the distance between the robot and the target was 67.27 cm, and the steering angle was detected -138.08º. In this position, the robot moves towards the target by changing its maneuver to the right, which is different from the two previous experiments. The reason the robot takes the right direction is because the steering angle has a minus sign, meaning fuzzy gives the left motor command faster than the right. The robot can reach the target within ± 86 seconds, and the robot stops when the robot's position approaches zero. Next, try the target in the fourth quadrant at the set point (60,-60). The system detects that the distance between the robot and the target is 84.85 cm, and the steering angle is -45.02º. The results of this experiment can be seen in Figure 7.d. Similar to the experiment in Figure 7.c, the robot maneuvers to the right towards the target. The time required to reach the target is ± 51 seconds. Mobile robots with differential drives based on fuzzy logic techniques are able to navigate towards specified targets. This experiment can be seen from the robot's smooth trajectory in reaching the target.



(a)



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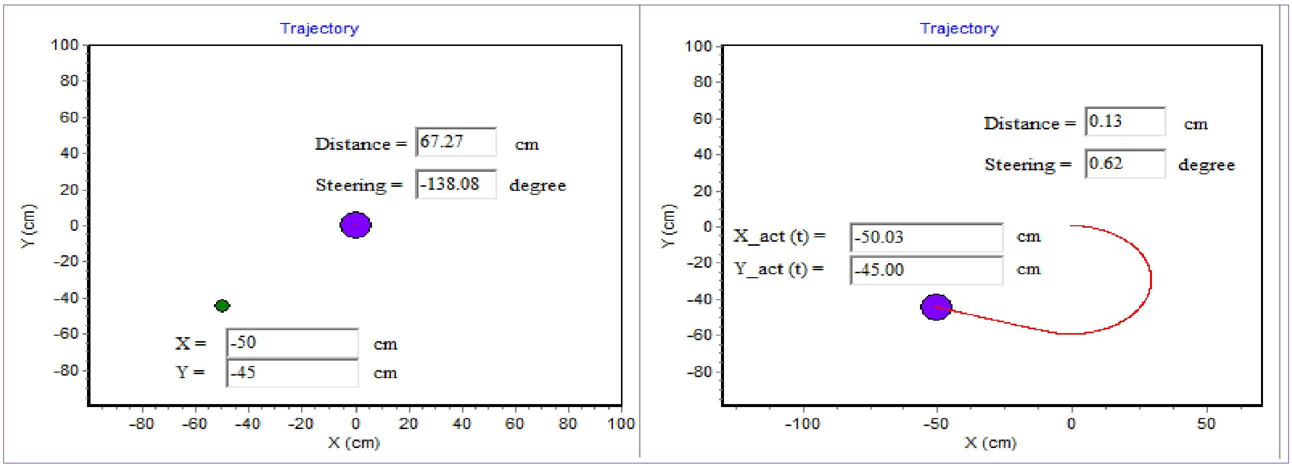
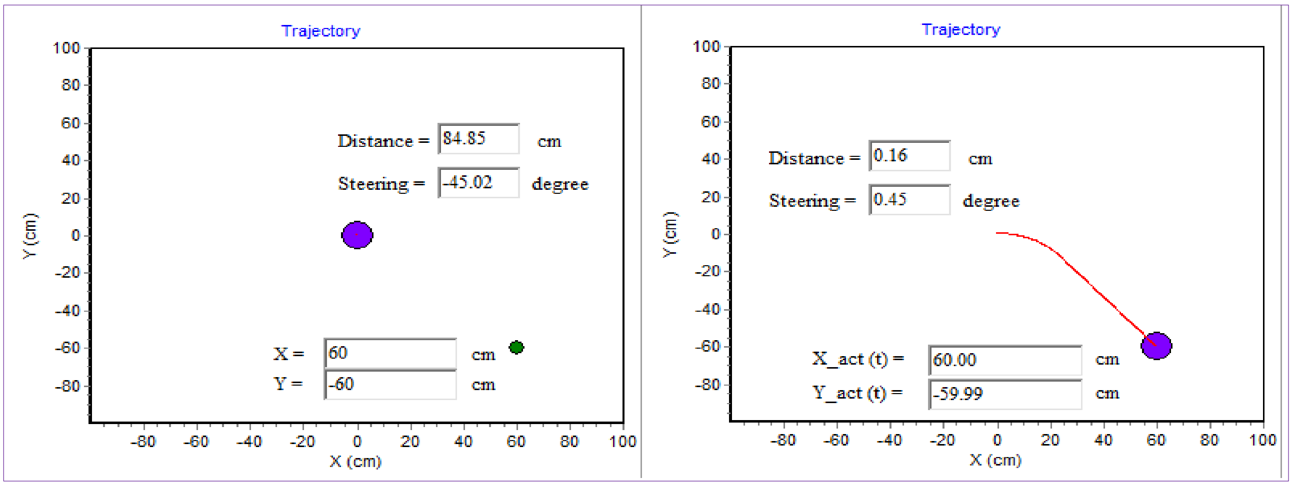
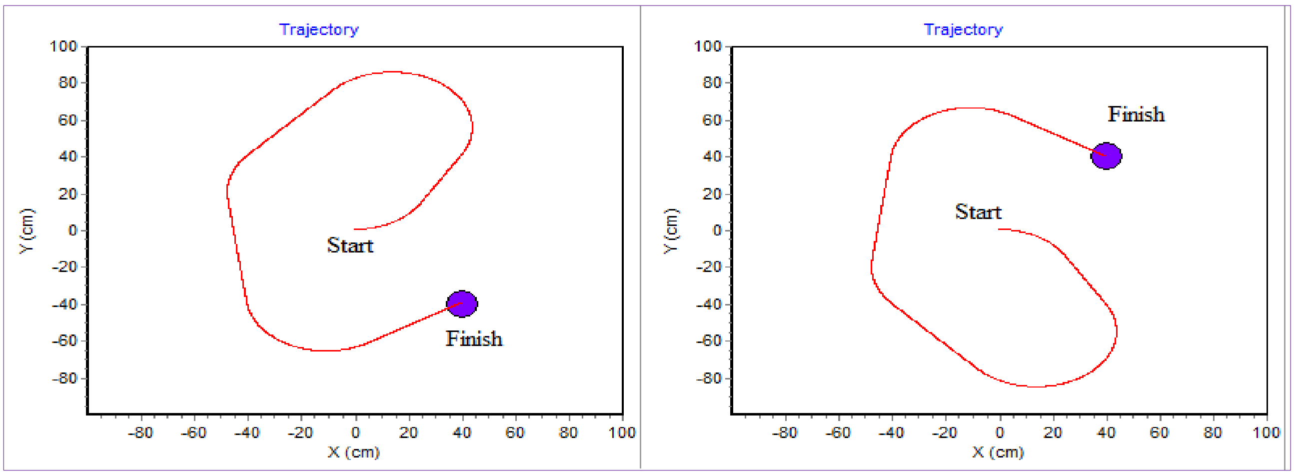


(c)



(d)

Figure 7. Robot trajectory towards the target. (a) set point (20, 40), (b) set point (-40, 60), (c) set point (-50, -45), and (d) set point (60, -60).



(a) (b)

Figure 8. The trajectory of the mobile robot towards many consecutive set points: (a) Set points from quadrants 1 to 4, and (b) the opposite.

The following experiment involved many set points, namely four targets representing each quadrant, namely (40,40), (40,-40), (-40,-40), and (40,-40). The results of this experiment are shown in Figure 8.a. The trajectory of this mobile robot moves to the right in the x-axis direction and then maneuvers to the left to reach

each target. Turn left because the system detects that the steering angle is positive. In this simulation, the robot moves smoothly toward each specified target. This experiment was also continued for set points from the opposite quadrant, namely 4 to 1 at (40,-40), (-40,-40), (40,-40), and (40,40). The results of this experiment are also shown in Figure 8. b. The mobile robot moves towards each target and is maneuvered to the right. Turn right because the system detects that the steering angle is minus. The time required for the robot to complete its mission is ±222 seconds for each experiment. From the results of this experiment, the differentially driven mobile robot implemented with fuzzy logic control can run smoothly toward the target.

V. CONCLUSSION

Mobile robots with differential drive are a type of robot that can move at high speed and have flexibility. Simulation of differentially driven mobile robots using a fuzzy logic control system is an exciting topic in the world of robotics. This simulation is in the form of a computer-based visual display. By using fuzzy logic, robots can process data from the surrounding environment more efficiently and accurately so they can make the right decisions in every situation they face. In this research, the robot can go to a predetermined target more smoothly and the trajectory with smooth movements. From the results of the simulations carried out, the application of a fuzzy logic control system in a mobile robot with a differential drive can improve robot performance significantly. Robots become more responsive and adaptive in interacting with the surrounding environment. Thus, the development and implementation of a fuzzy logic control system in a mobile robot with a differential drive has great potential to improve robot capabilities in various applications, such as in industry, health services, and agriculture. In addition, further research and development of this technology can also open up opportunities to create intelligent robots that can work independently and carry out complex tasks more effectively.

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