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The implementation of Mamdani Fuzzy Logic Control on a Hexapod Robot as a Guide for Visually Impaired People

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Abstract

The limitations of visually impaired individuals have encouraged innovations in human aid for them. One of those innovations is a robot that can act as guides for visually impaired individuals, and there are numerous studies focused on using robots as guides for them. However, these robots still face some limitations, particularly in navigating rough and uneven terrain. To handle this issue, we tried to develop a hexapod robot capable of traversing uneven surfaces more effectively than wheeled robots. The hexapod robot in this research is designed to be autonomous and employs fuzzy logic as its control method. The result shows that the hexapod robot has outstanding performance, attaining a 100% success rate in navigating the specified path and demonstrating a reliability of 79.78%.The constraints faced by visually impaired individuals have spurred various human-created innovations to aid them.One such innovation is the use of robots as blind guides.Numerous studies have explored using robots as guides for visually impaired individuals.However, these robots still face limitations, particularly in navigating rough and uneven terrain.

Keywords: visually impaired individuals, hexapod robot, autonomous robot, fuzzy logic.

I. INTRODUCTION

One of the essential senses for humans is the sight eye, which is used for seeing and then aiding in various activities. However, the eyes can experience impairments either completely (blindness) or partially, such as cataracts, myopia, presbyopia, hyperopia, and others. Blindness is a condition in which someone cannot see or is visually impaired. This, as it can disrupt daily activities.

The limitations faced by the visually impaired. These limitations have led to various human-created innovations to assist them. For example, there is research aiming. Previously, research has been conducted to create innovative canes with ultrasonic ping sensors that can help visually impaired individuals detect objects and surface heights in their surroundings [1], [2]. There are also innovative belts that use ultrasonic sensors to help visually impaired people detect objects around them [3]. However, these canes and belts have limitations for navigation as they can only perceive the environment within a limited range. Additionally, another approach for these limited ranges is that there are innovations in the form of wheeled robots that act as guides for the visually impaired individual [4], [5]. These robots help to find the correct and safe path. However, wheeled robots have limitations in uneven terrain and are limited to good terrain, so they have poor performance on uneven surfaces such as stairs, gravel paths, and undulating tracks.

On the basis of these issues, a legged robot is needed to guide the visually impaired in moving around. The hexapod robot is the most suitable design for this task. With its six legs, the hexapod robot has better balance and reliability in traversing undulating terrain compared to other robot shapes such as humanoid and quadruped [6]. Additionally, the designed robot is also expected to be able to work autonomously without being directly controlled using a controller.

One of the biggest challenges in creating an autonomous robot is the control and navigation system. This is influenced by various factors, such as sensors, microcontrollers, actuators, and control methods. The control methods used in robots each have their own weaknesses. For example, hexapod robots use behavior control methods that have weaknesses in maintaining robot distance stability with walls because the control is too rigid and disrupts robot movement flexibility [7], [8]. PID control methods are also used in other research, but they have weaknesses in parameter tuning that take a long time [9], [10]. Another method used is space detection algorithms, which have weaknesses in requiring several types of sensors to recognize space and take a long time [11]. The use of artificial intelligence as a control method is also complex and requires fast processors.

Fuzzy logic control methods are also used in the navigation control of hexapod robots, as is done by [12], [13]. This method has advantages such as lightweight computation so it can use microcontrollers, easier parameter tuning based on human logic, and less complicated program code with many decisions. In [14]

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we can see the trend of how fuzzy logic was used in the navigation of mobile robots in recent years, where we can see that the fuzzy logic controller for autonomous mobile robot navigation has played an important role in shaping academic research since its inception.

The use of fuzzy logic as a mobile robot controller to avoid obstacles was also discussed in [15], [16], which has shown that it works well in helping the robot maneuver around obstacles. It is very important that the robot performs well in maneuvering the obstacles if it is used to guide visually impaired people. Therefore, in this research, a hexapod robot with fuzzy logic control was created to guide visually impaired individuals. This research mainly focuses on the development of a more effective and versatile assistive device for visually impaired individuals by combining a suitable robot design (hexapod) with a robust and efficient control method (Mamdani fuzzy logic).

II. METHODS

A. Mechanical Design of the Robot

Ultrasonic sensors and SharpIR sensors are used to construct this hexapod robot's navigation system. To move the robot, actuators are used in the form of Dynamixel AX-18A servos, which are integrated with the output of the fuzzy control. Fuzzy control utilizes ultrasonic sensors and compass sensors as input variables to ensure the robot's stable movement when navigating walls. In general, the mechanical design of the robot can be seen in Figure 1.

The design of the robot legs can be seen in Figure 2, where the robot legs use three degrees of freedom. These degrees of freedom connect various parts of the robot's legs. There is a joint called the thoracic-coxal joint (TC-Joint) that connects the thorax and coxa, allowing forward and backward movement of the legs. Next, there is the coxa-trochanteral joint (CTr-joint) that connects the coxa with the femur, allowing for up-and-down movement of the legs. Finally, the femur-tibia joint (FTi-joint) connects the femur to the tibia, allowing the legs to expand and contract movements.

As for the design of the robot's body, it is made so that the robot can detect obstacles around it simultaneously. In this case, a ping sensor configuration is used, as seen in Figure 3, to reduce blind spots on the robot. Using more sensors would increase the detection capabilities but would decrease the efficiency and effectiveness of the readings. Therefore, in this robot design, only nine sensors are used. This number of sensors is sufficient to reduce the blind spots of the robot.

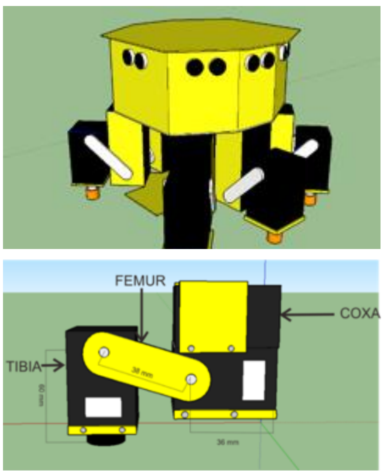

Figure 2. Mechanical design of the Robot Legs.

Figure 3. Ping Sensors Configuration of the Robot.

B. Electrical Design of the Robot

As shown in the block diagram of the robot's electronic circuit in Figure 4, the battery is used as the voltage source for the Teensy 4.0 microcontroller, the OpenCM9.04 microcontroller, and the 18 Dynamixel AX-18A servos, which are the main power source of the robot. Nine ping sensors are used to detect obstacles around the robot; however, ping sensors have limitations in detecting surfaces that absorb sound waves. Therefore, SharpIR sensors are also used to measure the distance to obstacles, similar to ping sensors but with better performance in detecting surfaces that absorb sound waves. All data obtained by the sensors are processed in the Teensy 4.0. The data from each sensor are stored alternately in specific variables before being processed in the next stage. Thus, the robot can detect obstacles around it, both solid and sound-absorbing. The CMPS12 sensor is used to measure the angle of the robot relative to the direction of the compass. In the master Arduino, all sensor readings are processed, including decision-making using fuzzy logic methods, resulting in data that will be sent to OpenCM9.04. Communication occurs between Teensy 4.0 and OpenCM9.04 through UART pins, where Teensy 4.0 sends foot movement data, and OpenCM9.04 acts as the data receiver. The OpenCM9.04 will control the Dynamixel servos to enable the robot to move. This robot used two microcontrollers to overcome the problem of crashes between sensor readings and dynamixel actuation.

C. Robot control design

As shown in Figure 5, the control method used for the robot is a closed-loop control system. The applied

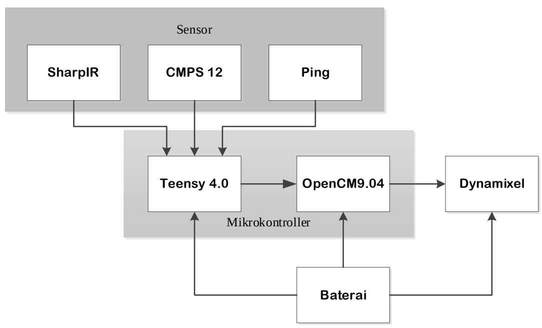

Figure 4. Electronic Circuit’s Block Diagram of the Robot.

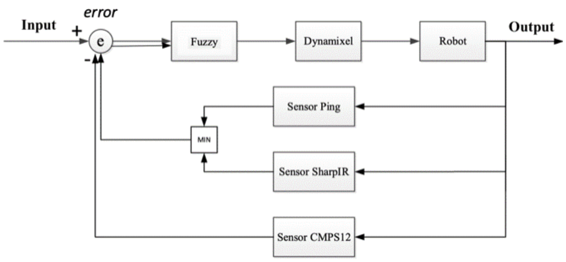

Figure 5. Control Design Block Diagram of the Robot.

control method is fuzzy logic, which regulates the operation of 18 AX-18 Dynamixel servos. These actuators are responsible for moving the robot's position. The robot reads its environment using sensors that also function as feedback to ensure that the robot's movement matches the desired outcome. The inputs for the fuzzy logic are the difference in the angle and distance parameters between the set point and their actual values. The set points used are 0 degrees for the angle parameter and 20 cm for the distance between the robot and the wall. The actual values for the distance and angle parameters are obtained from the Ping and CMPS12 sensors.

For the membership function in the fuzzy control of this robot, triangular membership functions are used. The selection of these membership functions is based on lightweight computations that can be executed on microcontrollers. In this fuzzy control design, there are two input variables and one output variable. The input variables consist of angle and distance. The values inputted for angle and distance are the difference between the measured value and the set-point value. This facilitates observing the response in simulations. Meanwhile, the output generated is data to increment the servo angle change width in the robot step. The input variables are divided into three sets of values, while the output variable is divided into five sets of values. The membership functions of the input distance and angle, as well as the output, were obtained through a trial-and-error process, where the values can be seen in Figure 6.

Based on the number of input variables and the variations used, there are at least nine basic fuzzy rules. In this fuzzy design, there are five output variations. The very negative variation will occur if the angle variable is positive and the distance variable is in the positive range. The negative variation will occur if the angle variable is at the set or negative value and the distance variable is in the positive range. The set variation will occur if the distance variable is at the set value. The positive variation will occur if the angle variable is at the set or positive value and the distance variable is in the negative range. Meanwhile, a very positive variation will occur if the angle variable is negative and the distance variable is in the negative range. Table 1 shows the fuzzy rules used in the robot control.

D. Fuzzy Logic

Fuzzy logic, developed by Lotfi Zadeh in 1965, extends Boolean logic through fuzzy sets, which generalize classical set theory. Introduce membership degrees, allowing the conditions to be true, false, or uncertain. This flexibility helps address inaccuracies and uncertainties in reasoning [17]. A fuzzy control system is a system that operates using fuzzy values and fuzzy logic. A fuzzy control system consists of four stages: fuzzification, inference engine, rule base, and defuzzification.

1) Fuzzification

The fuzzification stage is used to convert input values, which are typically numerical or crisp values, into fuzzy quantities. In the rule-based stage, the inference engine uses fuzzy logic rules to make decisions about the output based on inputs to the fuzzy system. Because the output from the inference engine is still fuzzy, the defuzzification stage is used to convert fuzzy values into crisp values that can be sent to the actuators of the system or controlled devices [18].

As illustrated in Figure 6, triangular membership functions are selected for their lightweight computational requirements, suitable for microcontrollers. The fuzzy control system uses two input variables, angle, and

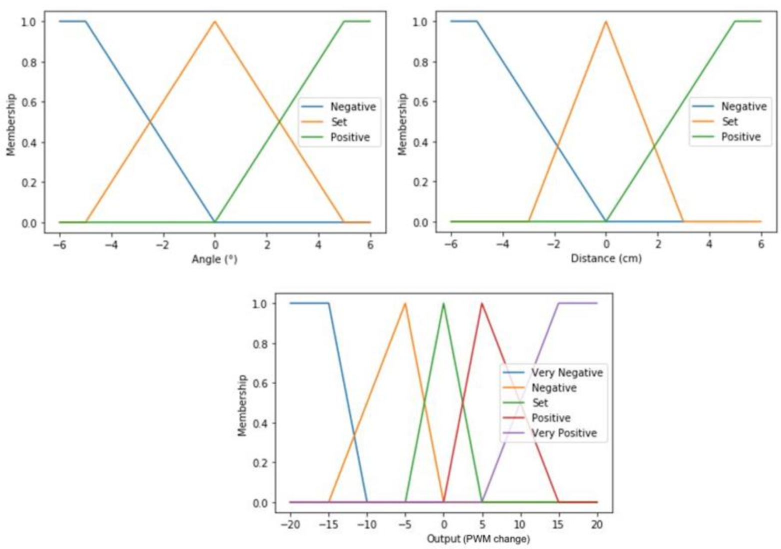

Figure 6. Membership Functions of Distance (cm), Angle (degree) and Output.

TABLE 1
FUZZY RULES USED IN THE ROBOT

Distance error	Angle error		
	Negative	**Set**	**Positive**
Negative	Very Negative	Negative	Negative
Set	Set	Set	Set
Positive	Positive	Positive	Very positive

distance, which reflect the difference between measured values and set points, allowing effective observation of the system response in simulations.

Meanwhile, the output is a value that increments the servo angle change in the robot step. The input variables are divided into three sets of values, while the output variable is divided into five sets of values. The membership functions of the input distance, angle, and output were obtained through a trial-and-error process, where the values can be seen in Figure 6.

2) Rules

There are at least nine fuzzy rules based on the number of input variables and the variations used. In this fuzzy design, there are five output variations. A very negative variation will occur if the angle variable is positive and the distance variable is in the positive range. The negative variation will occur if the angle variable is in the set or negative value and the distance variable is in the positive range. Set variation will occur if the distance variable is at the set value. The positive variation will occur if the angle variable is in the set or positive value and the distance variable is in the negative range. Meanwhile, a very positive variation will occur if the angle variable is negative and the distance variable is in the negative range. Table 1 shows the fuzzy rules used in robot control.

3) Fuzzy Inference

In this research, we used Mamdani fuzzy inference, which is a popular type of fuzzy inference system named after Ebrahim Mamdani, who introduced it in 1975. The advantage of using this type is that it is robust and flexible. It can handle uncertainty and imprecision in the input data, while it can also be easily adapted to various applications.

4) Defuzzification

We used the mean of maxima (MOM) for defuzzification, which is a common defuzzification method used in Mamdani Fuzzy Inference systems. It is a straightforward approach that involves calculating the average of the output fuzzy set's membership values at their maximum points. The formula of MOM can be calculated using the following formula:

$$MOM = \frac{\Sigma(\mu_i x_i)}{\Sigma\mu_i} \quad (1)$$

Figure 7. The Developed Hexapod Robot.

where MOM = the output value, μ_i = the membership value of the ith fuzzy set in the output, and x_i = the centroid of the ith fuzzy set.

III. RESULTS AND DISCUSSION

Following the design presented above, we managed to build the hexapod robot, as shown in Figure 7. We then performed the following tests to see the performance of the hexapod robot.

A. Testing of the Robot Walking Straight Along The Wall

This testing involved operating the robot indoors in a sufficiently spacious area, with one side having a flat surface. The robot was tested by moving it from one end of the side to the other. Three set points were used to adjust the distance between the robot and the wall, namely 10 cm, 15 cm, and 20 cm. For each set point, ten tests were conducted to evaluate the robot's ability to execute the command. The test results are documented in Table 2, where the success percentage is calculated from the successful experiment that happened compared to the total number of experiments performed for each distance. It can be seen that during the testing with the 10 cm set point, collisions often occurred as the robot moved along the wall, and there were three cases of failure out of a total of ten tests.

The test results for the 15 cm and 20 cm set points, as can be seen in Table 2, show that the testing went well for both set points, although for the 15 cm set point, there were still some collisions with the wall. However, from the overall results, it can be concluded that the 20 cm set point is the best choice to use because it yields better performance in carrying out tasks without significant collisions.

B. Testing of the Robot Walking Around a Miniature House

The previous testing results have determined that the best set point for the robot is 20 cm. In the next test, a

TABLE 2
RESULT OF THE ROBOT WALKING STRAIGHT ALONG THE WALL TEST

Distance (cm)	Max Distance Error (cm)	Min Distance Error (cm)	Max Angle Error (°)	Min angle Error (°)	Max of Collision for each test	Success percentage (%)
10	6	-5	40	-35	5	70
15	-1	-7	23	-23	2	100
20	3	-11	12	-19	0	100

simulation will be conducted in which the robot navigates around a miniature house. The miniature house has several corners representing house features. At this stage, fuzzy logic control will be implemented on the robot in the hope of making the robot's movement more stable. Figure 8 provides an illustration of the layout of the miniature house and the direction of movement of the robot.

The test results, documented in Table 3, indicate that the average travel time of the robot is 1 minute and 13 seconds. This travel time is considered relatively fast because of the robot's ability to navigate around the room. The average number of collisions that occur in each test is 5.8 times. This collision count is quite low considering the number of maneuvers that the robot must perform when moving in a dense area. The robot success rate in exploring the area reaches 100%.

C. Testing of the Guiding Respondents

This test aims to assess the effectiveness of the robot in performing the task of guiding the way for individuals with visual impairments. Three respondents have been involved in this test, where they were given several obstacles in the testing area. The respondents wore blindfolds and held a rope connected to the robot, simulating the situation of a visually impaired person using a guide dog. The obstacles used had several variations, with three different variations. The number of maneuvers performed by the robot varied between three to five times. Figure 9 shows one example of how this test performed.

The test results for the three respondents showed very good performance, as seen in the Table 4. However, in some testing processes, the robot often collides with obstacles. It can clearly be seen in the third test of the third respondent where the time it took for the robot to complete the route reached more than 60 seconds in which one of the tests took the robot more than 30 seconds to deal with the problem (bumping the wall). This could potentially disrupt the effectiveness of the robot in guiding the respondents to the end point of the test. However, the robot was still able to guide the respondents to the end point of the test.

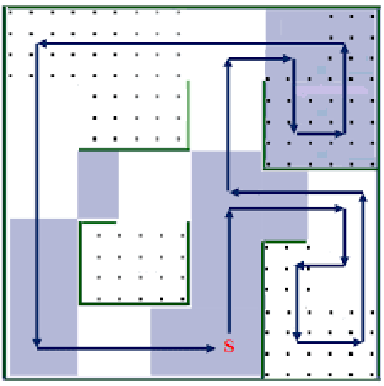

Figure 8. The Illustration of The Miniature House and The Path of The Robot.

Figure 9. The Robot-Guiding Respondent Test.

When comparing the failure time with the travel time, as shown in Table 4, the reliability level of the robot can be calculated using the following formula:

$$R = \frac{\Sigma t - \Sigma t_{trouble}}{\Sigma t} 100\% \quad (2)$$

$$= \frac{366 - 74}{366} 100\%$$

$$= 79.78\%$$

where R = the reliability level of the robot, Σt = the total of overall time, and $\Sigma t_{trouble}$ = the total time of trouble. It is shown that by using fuzzy logic control in the hexapod robot, we obtained 79.78% as the reability level of the robot. This reliability level is considered quite good considering the robot's 100% success rate in guiding the respondents.

IV. Conclusion

In this study, the developed hexapod robot has shown good performance when using the fuzzy control method with a set point of 20 cm. When tested with set points of 10 cm and 15 cm, incidents occurred where the robot collided with walls and often failed to complete its

TABLE 3
RESULT OF THE ROBOT WALKING AROUND THE MINIATURE HOUSE

Number	Time (s)	Collision	Result
1	76	5	Success
2	75	7	Success
3	69	4	Success
4	72	6	Success
5	73	7	Success
Average	73	5.8	

TABLE 4
RESULT OF THE ROBOT-GUIDING RESPONDENTS TEST

Respondent Number	Test Number	Result	Average time (s)	Trouble time (s)
1	1	Success	30	0
	2	Success	32	7
	3	Success	40	4
Standard Deviation			5.3	3.5
2	1	Success	30	0
	2	Success	28	6
	3	Success	47	10
Standard Deviation			10.4	5
3	1	Success	34	4
	2	Success	65	31
	3	Success	60	12
Standard Deviation			16.6	13.8

mission. However, when the robot used fuzzy control with a set point of 20 cm, it was able to move stably and never collided with walls. This indicates that the robot has a high level of stability. As for the testing of the robot's ability as a guide, the robot successfully guided all respondents with a success rate of 100% and a reability level of 79.78%. Although the robot sometimes still collided with walls, this did not result in mission failure.

DECLARATIONS

Conflict of Interest

The authors have declared that there are no competing interests.

CRediT Authorship Contribution

Mohamad Agung Prawira Negara: Conceptualization, Methodology, Writing-Reviewing and Editing; Fikri Mulyadi: Data curation, visualization, writing original draft preparation; Ali Rizal Chaidir: Investigation, Methodology, Writing-Reviewing and Editing; Khairul Anam: Conceptualization, supervision, project administration, acquisition of funds.

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