Design and Development of Assistive Canes for the Blind Based on IoT-Integrated Fuzzy Logic Using LiDAR Sensor Time of Flight VL53L1X

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***Abstract*— Visually impaired individuals often face difficulties in performing daily activities due to their limited visual senses. In order for the visually impaired to navigate without collision, a device with a system to detect obstacles in its surroundings is needed. In this study, a assistive cane has been designed that utilizes a fuzzy system based on the Mamdani model to detect obstacles. The main controller is an ESP32, equipped with two LiDAR VL53L1X sensors as inputs, capable of detecting obstacles up to 4 meters away. Family members can monitor the position of the visually impaired cane integrated with GPS through an Android application. The results of this study obtained an average error rate on the reading of two LiDAR Time of Flight Sensor devices with the VL53L1X type against obstacles in front of the stick of 0.00136% and sensor one has an accuracy of 99.85925% and sensor two has an accuracy of 99.862175% against the distance of obstacles in front of the stick. The blind cane made has an average battery life of 1 hour 35 minutes 83 seconds for random navigation, namely there are obstacles and no obstacles in front of the stick. Overall, the system can run well. The blind cane can classify the level of obstacles in front with the category of close at a distance of 0 - 100 cm, medium 101 - 150 cm, and far 150 - 400 cm.**

Keywords*— *Blind Stick, IoT, Sensor LiDAR, Fuzzy, Mamdani

I. INTRODUCTION

Generally, humans are born in good physical, social, and mental conditions. However, some humans are born with different conditions, one of which is an obstacle to vision that can interfere with daily activities. Individuals who experience visual impairments are referred to as blind people [1]. The impact of obstructed vision function is that blind people cannot obtain complete information about their surroundings. Humans can receive information about 80% of the environment through the sense of sight [2].

The traditional walking stick currently used by the blind provides assistance, but has some limitations. One example of a weakness is that the stick has to touch an object first so that the blind can know the distance between them and the object. The use of this cane also requires special skills through a structured training process, so that blind people can use the cane effectively [3].

In previous research, a blind wand has been developed that is capable of detecting nearby obstacles with the title "Design of Blind Assistive Devices Equipped with Obstacle Detection with Bluetooth Transmission and Sound Warning Systems", which is designed to use ultrasonic sensors to detect upper and lower obstacles and proximity sensors to detect obstacles. in the form of a hole with vibration output from a DC motor and sound from the speaker module [4].

Previously explained the use of internet of things (IoT) technology in research [5] [6] [7]. The use of IoT technology and GPS technology that is connected to an Android application on a blind stick will make it easier to track the position of a blind person who is traveling outside the area. Information regarding the position of the stick will be displayed visually through Google Maps, making it easier to find a search process that can be monitored by caregivers or relatives through an Android-based monitoring application [3].

II. METHOD

A. *Research Stages*

This type of research on the design of walking sticks for the blind uses research and development (R&D) methods. One of the research techniques used is interview, observation and development of Science and Technology which aims to gain insights related to certain topics. The design of this tool develops pre-existing research, and is expected to function according to the research objectives. This research discusses how to design a system for blind assistive devices based on Fuzzy logic, how the system works, how the components work, testing and analyzing the system to make a conclusion.

B. *Block Diagram*

Figure 1 below the power supply system is given to a 5V microcontroller which is generated from a lipo battery with a capacity of 3,500 mAh. The charger section uses the TP4096 charger module, which is used to recharge the battery when it runs out. Furthermore, the on/off switch is used to connect and disconnect electric current from the output of the TP4096 charger module with the ESP32 microcontroller.

The microcontroller used in this circuit is ESP32-Devkit V1 which serves as the brain of system data processing. LiDAR Time of Flight sensor type VL53L1X (lower position) is used to detect the lower obstacle of the stick and type VL53L1X (upper position) is used to detect the upper obstacle in front of the stick. The detection distance of the LiDAR Time of Flight sensor type VL53L1X ranges from 0 cm to 400 cm. The GPS module is used to send coordinate data, namely latitude and longitude, which will be sent to Firebase to be displayed in the form of a Google Maps map via the Android application. Microcontroller internet source via wifi tethering from a smartphone with visual impairments, with SSID configuration without a password. There are 2 types of output for the assistive canes for the blind, namely output in the form of sound stored on the SD card on the Opensmart speaker module and vibrations generated by a DC vibrator motor. The output sound "watch out for obstacles" will sound if the LiDAR Time of Flight sensor type VL53L1X and the vibration motor output will be processed on the mamdani model fuzzy system.

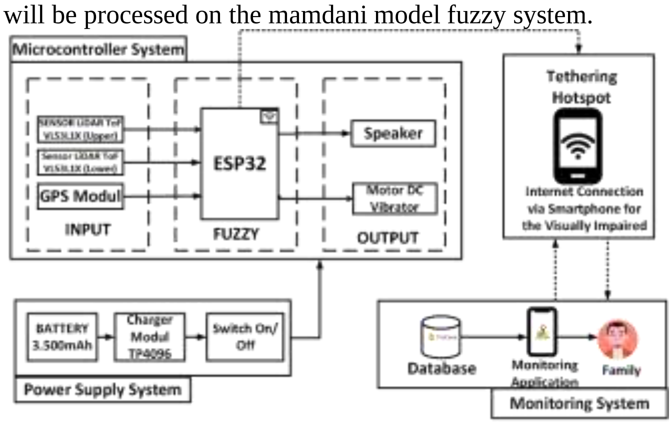


Figure 1 System Block Diagram

C. Sensor Time of Flight (ToF) VL53L1X

The VL53L1X is a proximity sensor component that uses a low-power laser beam as the medium. This sensor is used to measure the distance between the sensor and the object, with the calculation of the distance based on the time difference between sending the signal and receiving the signal back by the sensor. The signal sent is in the form of a packet consisting of microwaves with a distinctive pattern, so that the sensor can recognize these signals which have a range of up to 4 meters as shown in Figure 2 [8].

Figure 2 Sensor VL53L1X [9]

D. Modul GPS BN-180

The GPS system is designed to continuously track position in real-time regardless of weather or time conditions. GPS consists of three main parts, namely the satellite segment, the user segment, and the control segment. GPS positioning is based on four elements, namely the X, Y, Z coordinates, and the time parameter. By combining time information from several satellites, the GPS receiver can calculate the user's position with great accuracy. This information is used for navigation, mapping, research, and many other applications where accurate and continuous position monitoring is required [10]. GPS systems have become an important part of everyday life, helping people find their way, tracking vehicle movements, and providing assistance in emergency situations on figure 3.

Figure 3 Modul GPS BN-180 [11]

E. Microcontroller ESP32

ESP32 is an innovative and popular microcontroller developed by Espressif Systems, a technology company based in Shanghai, China. This microcontroller offers a reliable WiFi network solution, making it an ideal choice for Internet of Things (IoT) applications and electronics project development. With a powerful dual core processor and Xtensa LX16 instructions, ESP32 provides high performance and good energy efficiency. In addition, the ESP32 is also equipped with features such as Bluetooth, a rich sensor interface, and support for various communication protocols. Flexibility, strong network capabilities, and compatibility with various development platforms make ESP32 the first choice for developers to realize innovative ideas in the world of IoT and electronics [12] on figure 4.

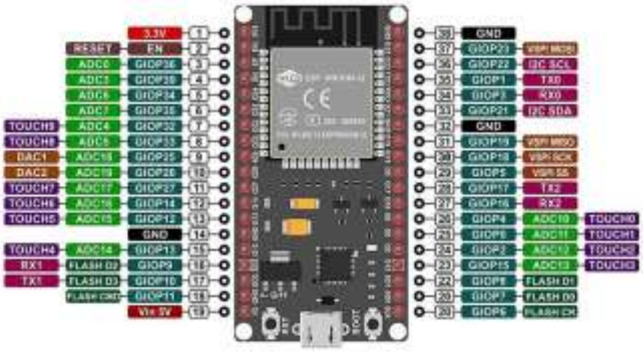


Figure 4 Microcontroller ESP32 [13]

F. Motor Vibrator

The vibrator motor is an electromagnetic device that converts electrical energy into mechanical energy. This motor requires a direct voltage supply to the magnetic field coil to be converted into mechanical energy on figure 5 [14].

Figure 5 Motor Vibration [15]

G. Modul Open Smart MP3

The Open Smart MP3 module is a serial MP3 component that perfectly combines MP3 integration and WMV hardware decoding. The accompanying software supports TF card drivers and FAT16 and FAT32 file systems. By using simple serial commands, this module can be used to play music and perform other functions without the need for complex operations. The advantage of this module lies in its ease of use, stability and reliability [16].

Figure 6 Modul Open Smart MP3 [17]

H. Blind Stick System Flowchart

Figure 7 is a picture of Flowchart System how to make a system blind stick.

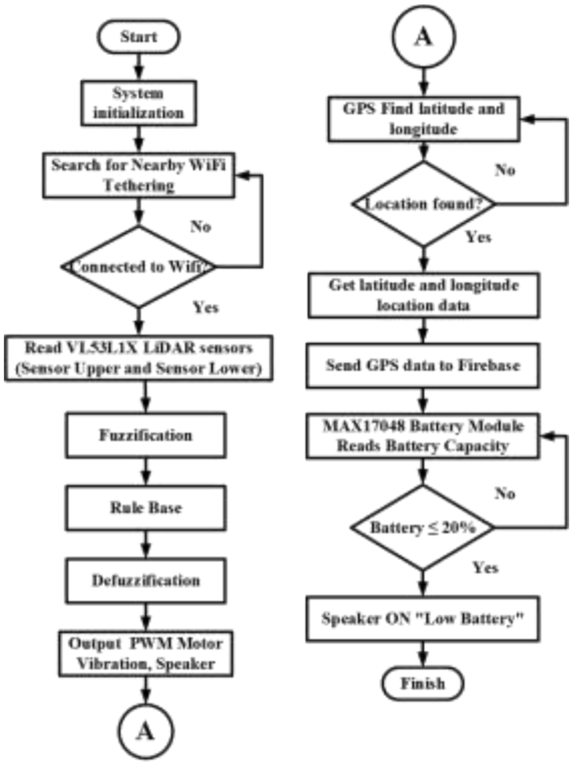


Figure 7 Flowchart System Blind Stick

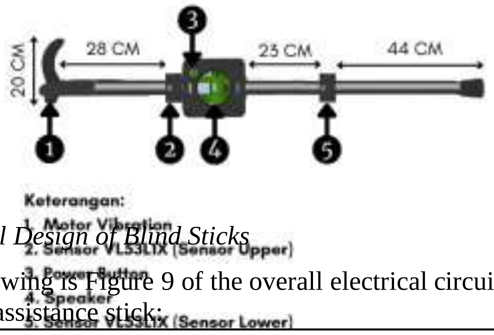
In accordance with Figure 7 Flowchart of the System Work Procedure, the steps for the work of the proposed tool are as follows: The ESP32 microcontroller gets electricity from a 3,500 mAh lipo battery and initializes the system via the on/off switch on the stick. The ESP32 microcontroller will process input data from the LiDAR VL53L1X sensor (lower position), VL53L1X (upper position), GPS Module, and MAX17048 Battery Module. If the LiDAR VL53L1X sensor (lower position) and LiDAR VL53L1X (top position) as obstacle detectors detect objects/objects reading distances below 100 cm the speaker will be active as an additional notification if there is an obstacle. Then it is processed using fuzzy logic method. Fuzzy logic includes the process of Fuzzification, rule evaluation, and defuzzification. After defuzzification, the PWM value output from the vibrating motor is obtained as a notification of an obstacle and an additional speaker notification will be active with a sound output "watch out for an obstacle". Conversely, if it detects above 100 cm, the speaker will die. The GPS module attached to the blind cane will look for latitude and longitude signals which are used as the basis for determining the position of the blind cane. If latitude and longitude signals are not found, the GPS module will continue to try to find signals. If the latitude and longitude signals are found, they will be processed by the ESP32 microcontroller to wait for the WiFi to be connected. If WiFi is connected, GPS data in the form of latitude and longitude will be sent to the Firebase database. The GPS data that has been received by Firebase will be sent to the Android application integrated with the Google Maps API and finished. The MAX17408 battery module is used to read the battery capacity if the remaining battery is below 20%, the speaker output will be active with the sound output "battery is low, charge immediately".

I. Mechanical Design of Blind Sticks

In the design implementation of the stick, it is explained how the microcontroller circuit is placed and the sensor positions used, including LiDAR Time of Flight sensors type VL53L1X (lower position) and VL53L1X (upper position), GPS module, lipo battery, and DC vibrator motor. The specifications of the stick used are also described in detail as follows.

1. Stick height: 120 cm
2. Stick length: 15 cm
3. Stick weight: 800 gr
4. Stick Material: Aluminum
5. Box Material: 3D Print Filaments

The following is the mechanical design of the blind stick implemented in Figure 8.



J. Electrical Design of Blind Sticks

The following is Figure 9 of the overall electrical circuit of the blind assistance stick:

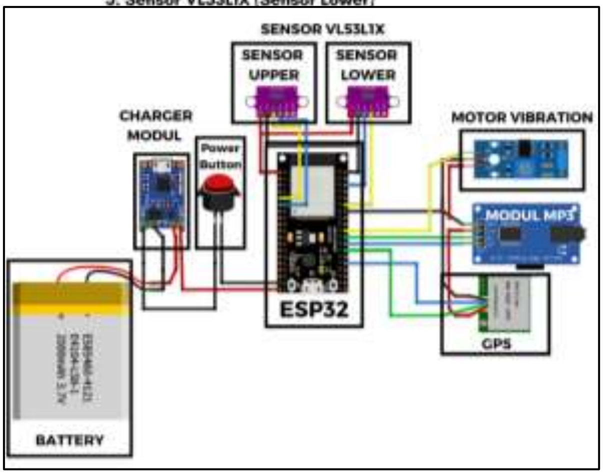


Figure 9 Electrical Design

K. Determination of Fuzzy Logic Rules

Fuzzy logic planning involves determining the rules that must be met to achieve the expected output. The method used in this planning is fuzzy logic, which uses fuzzy concepts for decision making based on predetermined inputs. There are three types of fuzzy methods, namely Fuzzy Mamdani, Sugeno, and Tsukamoto. In this study, the fuzzy method used is Fuzzy Mamdani because it has a lower error rate and is a method that is easier to understand, because it conforms to the human way of thinking and produces output in the form of real numbers.

The process of making fuzzy logic software begins with determining the input and output. In the plan used, there are two inputs, namely the distance of the upper sensor and the lower sensor (VL53L1X LiDAR sensor), while the output is the vibration speed of the vibration motor.

L. Determination of fuzzy logic input rules

In planning this system there are 2 fuzzy logic inputs, namely the distance from the upper obstacle sensor and the lower obstacle sensor (VL53L1X LiDAR sensor). Determination of the range of inputs based on the results of discussions with blind assistants at the UPT. Rehabilitation for the Blind City of Malang, namely the stick detects objects from a distance of 0 cm to 200 cm, which is used as a reference number for determining fuzzy rules in making fuzzy membership values with an output to activate motor vibration. The following is an overview of the fuzzy input chart:

1. Determination of the degree of distance input on the upper obstacle sensor

Figure 10 shows the distance range and the Mamdani fuzzy logic-based variables used, implemented through the MATLAB application. This provides a visual representation of how the distance ranges are classified in the categories defined using fuzzy logic on the sensor detection system mounted on top of the blind cane.

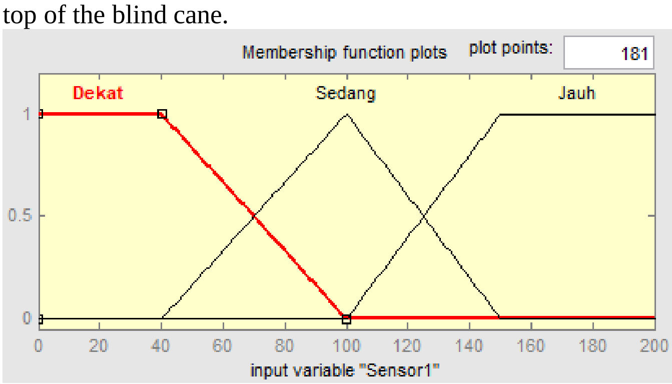


Figure 10 Degrees of Membership Upper Barrier Distance Sensor Input

Table 1 shows the distance variables and membership values included in the fuzzy logic variables, this data is a VL53L1X sensor attached to the top of the stick. This is to make it easier to categorize distance based on three categories, namely far, medium and near.

TABLE 1
UPPER BARRIER DISTANCE SENSOR DATA VARIABLE

Function	Variable	Membership
Upper obstacle distance sensor	Near	[0 0 40 100]
	Medium	[40 100 150]
	Far	[100 150 200 200]

2. Determination of the degree of distance input on the lower obstacle sensor

Figure 11 shows the Mamdani fuzzy logic-based distance ranges and variables, implemented through MATLAB application with distance categories of far, medium, and near. This aims to visually represent how the distance ranges are classified in the defined categories using fuzzy logic on the sensor detection system installed under the blind cane.

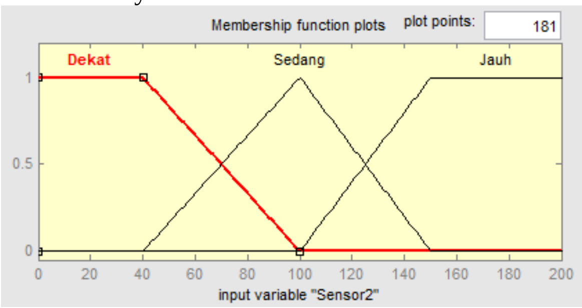


Figure 11 Degrees of Membership Input Distance Sensor Lower Obstacle

Table 2 shows the distance variables and membership values included in the fuzzy logic variables, this data is a VL53L1X sensor attached to the bottom of the stick. This is to make it easier to categorize distance based on three categories, namely far, medium, and close to detect obstacles under the stick.

TABLE 2
LOWER OBSTACLE SENSOR DISTANCE DATA VARIABLE

Function	Variable	Membership
Upper obstacle distance sensor	Near	[0 0 40 100]
	Medium	[40 100 150]
	Far	[100 150 200 200]

3. Determination of the degree of fuzzy logic motor output

After testing the vibrating motor, the vibration on the motor used is 255 with the fast variable, while for the silent variable it is 0-20. From these references, the planning of the output of the vibrating motor is as follows. As shown in the Figure 12.

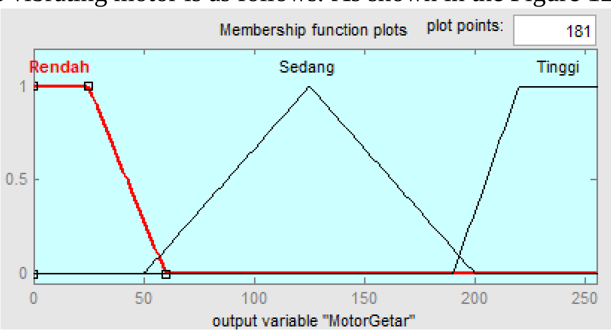


Figure 12 Vibration Motor Output Membership Degrees

E. Determination of Fuzzy Rules

Determine the fuzzy rules that are expected to be able to process input parameters so as to obtain the desired output results. The determination of fuzzy in the matlab application is shown in Figure 13.

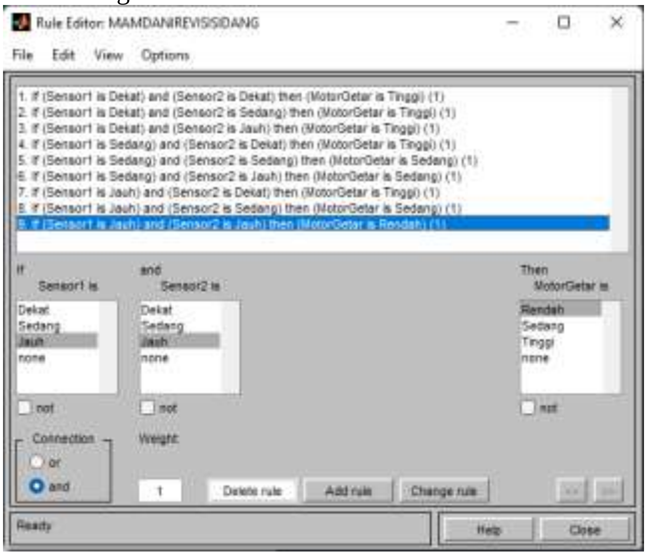


Figure 13 Rules Fuzzy Matlab

M. Determination of Defuzification Method

Next is the defuzzification stage using the centroid method. The choice of this method is based on the centroid defuzzification method which is relatively easy to implement and requires simple computations. This reduces the computational load on the fuzzy system, allowing for better performance and faster response times. With equation 1 as follows:

$$\text{COA } Z^* = \frac{\int u_x(z).\, zdz}{\int u_x(z)dz} \qquad 1$$

III. RESULTS AND DISCUSSION

A. Hardware Making Results for Blind Sticks

The following is the result of a mechanical manufacture for a blind cane made of aluminum and a cane box made of PLA from a 3D Printer print with a size of 7 cm x 7 cm and a thickness of 2 mm. This system uses the ESP32 microcontroller as data processing. As shown in the Figure 14.

Figure 14 Blind Cane Results

In the results of this blind assisting stick, on the outside of the stick box there are 2 VL53L1X sensors which function to detect objects, as well as 1 switch button to turn the system on and off, and a speaker to provide a warning indicator when an obstacle is detected. On the inside of the stick there is a GPS module that functions to send the location of the blind stick in the form of latitude and longitude. Then there is the battery as the system's power supply. Furthermore, there is an ESP32 microcontroller as data processing. At the top of the stick there is a vibrating motor which functions to provide an indicator when the distance is too close which is obtained from the VL53L1X sensor distance data using the fuzzy logic method.

B. Software Making Results for Blind Sticks

In the Android application, there is a feature to display the position of the blind via the GPS module attached to the stick sent by the ESP32 Microcontroller. Making this Android application uses Kodular, a web-based application. The choice of Kodular in this study is due to its ease in the manufacturing process, where users do not need to write code manually, but simply compile logic blocks with an easy-to-understand interface. The following is the result of planning an Android application to monitor the position of blind people integrated with the internet of things. As shown in the Figure 15.

Figure 15 results of making the blind stick monitoring application

C. VL53L1X LiDAR Sensor Test Results

The test results on the VL53L1X LiDAR sensor (both in the upper and lower positions) were obtained using data read by the system with a measuring device 1 meter away. The test was conducted 40 times to ensure accuracy and consistency. The results of these tests are then presented in Table 3 to provide a clear picture of the sensor's performance under various repetitive test conditions. The test uses a meter that measures the distance from the obstacle in front to the blind cane. This aims to determine the percentage level of accuracy of the VL53L1X LiDAR sensor with a meter measuring instrument as a comparison. To determine the accuracy value, the difference between the distance read on the sensor and the meter measuring instrument is used, so that the error value is obtained on sensor 1 VL53L1X (top position) and sensor 2 VL53L1X (bottom position). As shown in Figure 4.16.

TABLE 3
TESTING SENSOR VL53L1X

Testing	Result Measuring Instrument (cm)	Measured Results Sensor VL53L1X (cm)		Error(%)	
		Sensor 1	Sensor 2	Sensor 1	Sensor 2
1	10 cm	10 cm	10 cm	0 %	0 %
2	20 cm	20 cm	20.2 cm	0 %	1 %
3	30 cm	30 cm	30 cm	0.3 %	0 %
4	40 cm	40 cm	40.5 cm	0.75 %	1.25 %
5	50 cm	50 cm	50 cm	0 %	0 %
6	60 cm	60 cm	60.1 cm	0.66 %	0.16 %
7	70 cm	70 cm	70 cm	0 %	0.14 %
8	80 cm	80 cm	80 cm	0 %	0 %
9	90 cm	90 cm	90 cm	0.88%	0%
10	100 cm	100 cm	100 cm	0 %	0 %
Average Error Rate (%)				0,25 %	0,25%

Figure 16 Measurement With Meter

Data collection was carried out with 10 trials at a distance of 10 cm to 100 cm because the sensor is only able to read up to a distance of 1 meter or 100 cm. The test uses the meter as a comparison tool. Repetition of 10 experiments provides an average accuracy of the distance detected by the LiDAR VL53L1X sensor (sensor 1 and sensor 2) with the comparison tool used.

Accuracy Percentage of Sensor 1 Distance	=	100% - Average Percentage Error
	=	100% - 0.25%
	=	99,75%
Accuracy Percentage of Sensor 2 Distance	=	100% - Average Percentage Error
	=	100% - 0.25%
	=	99,75%

D. Fuzzy Logic Testing

The following is a system test using fuzzy logic, this test aims to determine the fuzzy, rule, and defuzzification work systems and to find out the results of the comparison of vibrating motor speeds on the results of fuzzy calculations using the Matlab application. As shown in Table 6.

TABLE 6
DEFUZZIFICATION OF MEASUREMENT RESULTS IN MATLAB AND HARDWARE

No	Sensor VL53L1X (cm)		Defuzzification		Obstacle Category
	Sensor Upper	Sensor Lower	Matlab	Hardware	
1	20	20	220	220,2	Near
2	42	37	230	230,3	Near
3	100	105	7,13	7,10	Medium
4	120	110	7,13	7,12	Medium
5	79	78	131	131,1	Near
6	92	90	115	115,6	Near
7	49	45	136	136,3	Near
8	54	52	115.7	115	Near
9	65	65	135	135,7	Near
10	7	10	254,7	255	Far

From the data defuzzification results in table 6 it is done by comparing the values generated by the hardware with Matlab. It can be seen from the tests that have been carried out 10 times with different distances. Matlab defuzzification results have a greater difference than hardware defuzzification. With the smallest difference in value, namely 0.1 in experiment 5 and the largest difference in results in experiment 9, namely 0.7. Based on the results of the fuzzy test on Matlab, there is a small difference, so that the planning with the test results has gone well.

1. Fuzzy Test Results on Hardware

In testing based on hardware, a defuzzification value of 220,2 was obtained with the output value on vibrating as shown in the Figure 17:

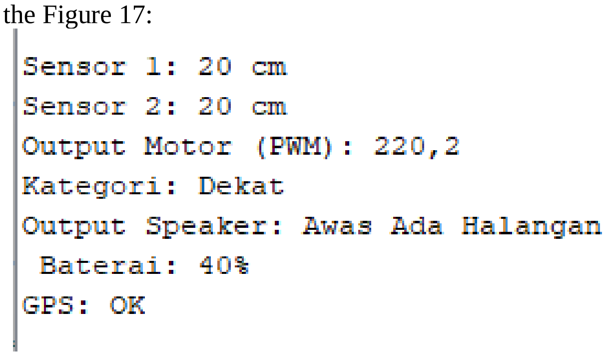


Figure 17 Fuzzy testing on hardware

2. Fuzzy Test Results on Software

In tests based on simulations using Matlab software, a defuzzification result of 220 was obtained in the vibrating category. This information is documented in Figure 18, which displays the simulation results visually. The defuzzification value indicates the level of vibration produced by the system based on the input data received and the fuzzy logic process applied.

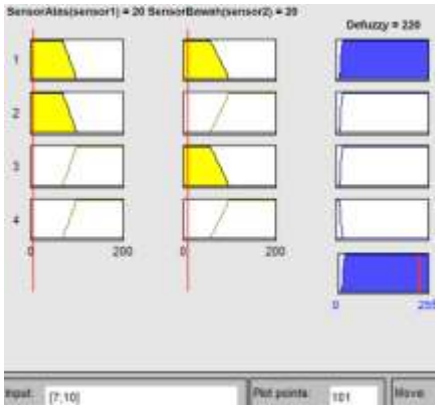


Figure 18 Fuzzy Testing Based on Matlab Simulation

E. Testing The Overall Navigation of The Blind Cane System

Testing the entire system is carried out to test the performance and battery life of the IoT-integrated Fuzzy Logic-Based Blind Assistive Stick system using the VL53L1X Time of Flight LiDAR Sensor.

In the third overall system test is testing no obstacles and obstacles around a blind stick which aims to test battery life when the speaker output is active or inactive, and the motor vibrates according to the category of obstacles near, medium, and far. In this system, the battery used is Li-Po (Li-Polymer) type and has a capacity of 3,500 mAh with a working voltage of 5VDC. Testing was carried out 10 times randomly with obstacle conditions in front of the stick, this aims to determine the sensitivity of the VL53L1X sensor integrated in the blind cane. As shown in Figure 4.19.

Figure 19 Testing Navigation in The Presence of Obstacles

Figure 4.20 shows a series of tests performed on a blind stick. The test was repeated 10 times without any obstacles placed in front of the stick. The purpose of this test is to thoroughly evaluate and determine the sensitivity level of the VL53L1X sensor integrated in the blind cane. Each repetition of the test was thorough and organized, creating consistent conditions for collecting accurate data. This allowed for an in-depth analysis of the sensor's performance in various situations. By conducting the test 10 times, enough data could be generated to obtain a representative picture of the sensor's sensitivity. Repeating the tests without any obstacles in front of the blind stick ensured that each test was conducted under similar conditions, so that the results could be compared consistently. The data collected from this test will be an important foundation in the evaluation of the quality and performance of the blind cane and its VL53L1X sensor. As such, this test plays a crucial role in measuring and verifying the reliability of the VL53L1X sensor in detecting distance without any external interference. The results of this test will provide valuable insights for the development and improvement of technologies related to the use of blind canes as assistive devices for individuals with special needs.

Figure 20 Testing Navigation When There is No Obstacle

Shown in Figure 4.21 testing the battery life integrated in the blind cane which aims to determine the usage time of the blind cane from a fully charged battery until it runs out, measuring the battery using a stopwatch measuring instrument.

Figure 21 Overall Stick Battery Power Testing with a Stopwatch

Shown in Figure 4.22, the tool program output is displayed via a serial monitor using the Arduino IDE application. The output includes the value of the VL53L1X sensor measured in centimeters, information about the vibration value of the vibrator motor in PWM units, and the distance category generated by the sensor based on fuzzy logic. This displayed data provides a deeper understanding of the tool's performance and how the VL53L1X sensor interacts with the vibrator motor in generating a response that corresponds to the detected distance. This allows for proper monitoring and adjustment in the use of the tool according to the desired needs.

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Sensor 1: 172 cm
Sensor 2: 171 cm
Output Motor (PWM): 13
Kategori: Jauh
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Figure 22 Arduino IDE Serial Monitor Output on Blind Stick Navigation Testing

Table 7 shows the results of testing battery life always without obstacles or obstacles with far, medium, and near categories. With the speaker output not on or on and the intensity of the motor speed vibrates according to the obstacle category.

TABLE 7
TESTING THE OVERALL NAVIGATION OF THE BLIND CANE SYSTEM

No	Distance (cm)		Obstacle Category	Vibrating Motor Speed (PWM)	Speaker	Battery Time Out
	Sensor Upper	Sensor Lower				
1	172	171	Far	13	-	1 Hour 25 Minutes
2	46	44	Near	228	✓	52,45 Minutes
3	120	123	Medium	184	✓	53,21 Minutes
4	31	28	Near	243	✓	45,14 Minutes
5	188	191	Far	9	-	1 Hour 27 Minutes
6	181	181	Far	11	-	1 Hour 25 Menit
7	192	190	Far	6	-	1 Jam 30 Minutes
8	167	166	Far	17	-	1 Hour 23 Minutes
9	105	103	Medium	181	✓	41,43 Minutes
10	4	5	Near	255	✓	36,33 Minutes
Average time the battery runs out						1 Hour 35 Minutes

The test results shown in table 7 show the average battery usage until it runs out on the actual blind cane with a stopwatch measuring instrument, namely for 1 hour 35 minutes and near, medium, and far obstacle conditions that are done randomly.

IV. CONCLUSION

Through various testing and data collection processes, conclusions can be drawn, as follows:

The obstacle detection system performed by the LiDAR Time of Flight sensor with type VL53L1X by comparing the actual distance using a measuring instrument has an average error rate of 0.14075% for the upper sensor which has an accuracy of 99.85925% and the lower sensor for 0.13825% which has 99.862175% accuracy. The blind cane can be monitored through an Android application that integrates GPS on the cane with internet access via tethering hotspot from the blind person's smartphone. The blind cane made has an average battery life of 1 hour 35 minutes 83 seconds for random navigation, namely there are obstacles and no obstacles in front of the stick.

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