

Design and Development of a Floor Cleaning Robot with Fuzzy Automatic Control and IoT Integration

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Abstract— The development of automation technology and the Internet of Things has encouraged the need for floor cleaning devices that can operate independently and be easily controlled by users. This research designed and developed an ESP32-based floor cleaning robot with a navigation system based on the Mamdani fuzzy logic method and IoT integration. The robot uses three HC-SR04 ultrasonic sensors placed on the left, center, and right sides to detect obstacles. Sensor distance data are processed through fuzzification, fuzzy rule inference, and defuzzification to determine the robot movement direction, namely turning right, moving straight, or turning left. The cleaning mechanism uses brush motors and a vacuum, while an Android application is used to activate automatic mode, control cleaning components, monitor battery status through Firebase, and provide manual control through Bluetooth. Fuzzy system testing showed an average error of 0.51% between manual calculation and MATLAB simulation. Cleaning performance testing showed an average effectiveness of 49.67% in automatic mode and 78.67% in manual control mode. The results indicate that the fuzzy system can support autonomous navigation, while manual control provides higher cleaning effectiveness because users can direct the robot toward remaining dirt areas.

Keywords— *Android, Bluetooth, ESP32, Firebase, Floor Cleaning Robot, IoT, Mamdani Fuzzy Logic, Ultrasonic Sensor.*

I. INTRODUCTION

The rapid development of technology has brought significant changes in everyday life, including in cleaning activities[1]. Floor cleaning activities that should be carried out routinely are often neglected due to limited time and energy. In this context, floor cleaning robots become a relevant solution because they can perform cleaning tasks independently without requiring direct human intervention. Research on floor cleaning robots has demonstrated the use of ultrasonic sensors, cleaning brushes, and vacuum mechanisms to automate dust collection and floor cleaning processes[2]. The development of autonomous floor cleaning robots has also incorporated obstacle detection, wireless control, and multiple operating modes to reduce the need for direct human intervention[3].

Currently, autonomous floor cleaning robots require reliable navigation systems to avoid obstacles and improve cleaning coverage. Previous research has shown that fuzzy logic can be applied to mobile robot navigation because it can process uncertain distance information and generate appropriate movement decisions[4]. A Mamdani fuzzy controller using multiple ultrasonic sensors has also been implemented for obstacle avoidance in wheeled mobile robots, demonstrating that distance information from different directions can be used to determine robot movement[5]. Other research has implemented three ultrasonic sensors positioned at different angles on a differential-drive mobile robot and successfully used Mamdani fuzzy logic for obstacle avoidance [6]. These studies indicate that fuzzy logic combined with ultrasonic sensing is suitable for autonomous navigation in indoor environments.

Implemented Mamdani fuzzy logic for an automatic water drainage system using temperature and turbidity as input variables to determine the valve operating time. The study applied fuzzification, Mamdani fuzzy rules, and defuzzification to produce the control output, demonstrating the application of Mamdani fuzzy logic in an automatic control system based on multiple sensor inputs[7]. However, the application of Mamdani fuzzy logic for floor cleaning robots using multiple ultrasonic sensors to determine navigation actions remains an area that requires further development.

On the other hand, the integration of the Internet of Things (IoT) provides an opportunity to improve the remote monitoring and control capabilities of cleaning robots. ESP32 is widely used in IoT applications because it provides integrated Wi-Fi and Bluetooth connectivity, enabling communication between embedded devices and remote monitoring systems[8]. Previous research demonstrated the implementation of ESP32 with Wi-Fi to support real-time monitoring and remote control through an IoT dashboard[9]. Therefore, integrating autonomous navigation with IoT-based monitoring and manual control can provide greater flexibility for users.

Based on these considerations, this research develops a floor cleaning robot that combines Mamdani Fuzzy Logic for autonomous obstacle avoidance, three ultrasonic sensors for distance detection, and an ESP32-based IoT system for remote monitoring and control. The robot also provides automatic and manual operating modes, allowing its cleaning performance to be evaluated under both operating conditions.

II. METHOD

A. Research Design

This research used an engineering method with a quantitative experimental approach. The research stages consisted of literature study, system design, hardware and software implementation, sensor calibration, fuzzy system, cleaning performance testing, Android-Firebase testing, Bluetooth manual control testing, and data analysis. The robot was designed for indoor flat floors and was not intended for carpeted surfaces, stairs, outdoor areas, wet dirt, or complex narrow obstacles.

B. System Architecture

The main controller used in the system was an ESP32 microcontroller because it supports Wi-Fi and Bluetooth communication[10]. The input system consisted of three HC-SR04 ultrasonic sensors installed on the left, center, and right sides of the robot[11]. The output system consisted of DC motors for mobility, front and middle brush motors, and a vacuum motor for collecting dry dirt. Battery voltage was monitored using a voltage divider circuit[12], and transmitted to Firebase so that the Android application could display the battery percentage in real time[13].

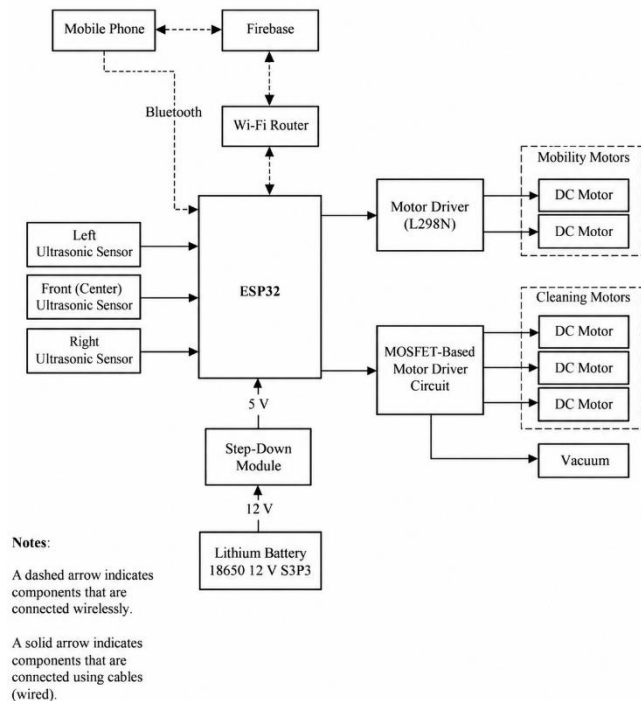


Figure 1. System architecture of the proposed floor cleaning robot

Figure 1. Shows that the power system uses lithium 18650 batteries as the main supply. A step-down module is used to provide a stable voltage level for the ESP32 and supporting electronics. The motor driver L298N is used to control the

direction of the mobility motors, while separate switching circuits are used for the cleaning actuators. This separation is necessary because the drive motors and cleaning motors have different current requirements.

The mechanical structure was designed as a compact circular robot with a diameter of approximately 29 cm and a height of approximately 12 cm. The front brush mechanism collects dust and sand toward the middle area, while the middle brush directs dirt toward the vacuum inlet. The vacuum motor then pulls dirt into the dust container. This arrangement was selected so that sweeping and suction occur in sequence during robot movement.

The sensor placement was arranged to support navigation decisions. The center sensor detects obstacles in front of the robot, while the left and right sensors provide side distance information. This configuration allows the fuzzy system to compare which side is safer when the front direction is blocked. Although this three-sensor configuration is simple, it is sufficient for basic obstacle avoidance in a flat indoor testing area.

The Android application provides automatic mode, cleaning component control, battery monitoring, and manual movement control. In automatic mode, commands are sent through Firebase and the robot performs navigation based on fuzzy logic. In manual mode, the smartphone sends Bluetooth characters to the ESP32. The characters F, B, L, and R represent forward, backward, left turn, and right turn commands, respectively.

C. Wiring dan Pin Configuration

The wiring and pin configuration of the proposed floor cleaning robot were designed to connect the ESP32 with the ultrasonic sensors, motor driver, cleaning actuators, and battery monitoring circuit. The ESP32 serves as the main controller, receiving distance information from the ultrasonic sensors and sending control signals to the motor driver and cleaning motors. The wiring arrangement of the hardware system is shown in Figure 3.

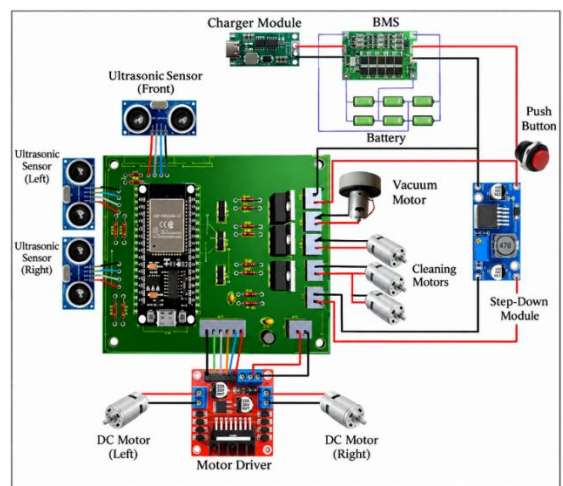


Figure 2. Wiring diagram of the proposed floor cleaning robot.

The three ultrasonic sensors are connected to the ESP32 to provide distance information from the center, left, and right directions. The center ultrasonic sensor uses GPIO 12 for the Trigger pin and GPIO 14 for the Echo pin. The left ultrasonic sensor uses GPIO 4 for Trigger and GPIO 18 for Echo, while the right ultrasonic sensor uses GPIO 5 for Trigger and GPIO 17 for Echo. The sensors are supplied with 5 V and share a common ground with the ESP32.

The L298N motor driver is supplied by the 12 V battery system and is controlled by the ESP32. The IN1, IN2, IN3, and IN4 pins are connected to GPIO 18, GPIO 19, GPIO 22, and GPIO 23, respectively, while ENA and ENB are connected to GPIO 32 and GPIO 33. The separate MOSFET driver circuit is used to control the vacuum and three brush motors. The vacuum motor is controlled through GPIO 27, while the cleaning motors are controlled through GPIO 25 and GPIO 26.

Battery voltage monitoring is performed through GPIO 35, which functions as an ADC input. The battery voltage is measured through a voltage-divider circuit before being read by the ESP32.

D. Hardware Design

The hardware design of the proposed floor cleaning robot was developed using acrylic material as the main material for the robot body. Acrylic was selected because it is relatively lightweight, sufficiently rigid for the robot structure, easy to cut and shape, and provides a suitable surface for mounting the electronic and mechanical components. The robot body is designed in a circular shape with a diameter of approximately 29 cm and a height of approximately 12 cm.

The acrylic material is used to form the main body and cover of the robot. The structure consists of an upper and lower section that are assembled using bolts and nuts to make the construction firm while allowing the upper cover to be opened when maintenance or inspection is required. In addition, several mechanical parts are attached to the acrylic body to support the operation of the cleaning mechanism. The physical design of the proposed floor cleaning robot is shown in Figure 4.

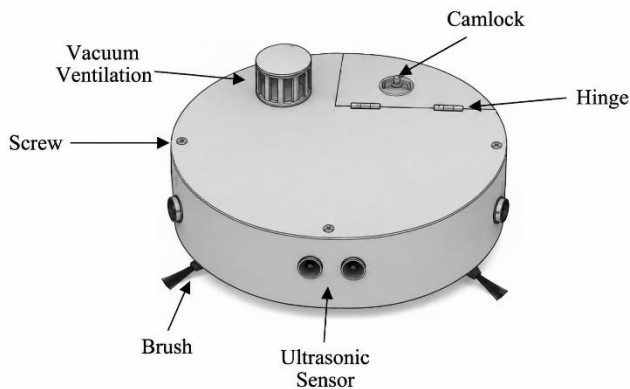


Figure 3. Hardware design of the floor cleaning robot

E. The design of the Mamdani fuzzy logic system

In this study comprises three main stages: fuzzification, rule-based inference, and defuzzification. These stages are used to process distance data obtained from ultrasonic sensors into decisions regarding the robot's movement direction for obstacle avoidance. The system inputs are derived from three ultrasonic sensors mounted on the left, center, and right sides of the robot, while the system output is the robot's movement direction: Turn Right, Straight, or Turn Left.

1) Fuzzification:

Fuzzification is used to convert ultrasonic sensor distance values—which are crisp values—into fuzzy membership degrees. The input domain for each ultrasonic sensor ranges from [0, 80]cm and is divided into three fuzzy sets: Near, Medium, and Far. The mathematical equations for the membership functions of each set are defined as follows:

a) Near Set (Trapezoidal shape [0, 0, 20, 35]):

$$\mu_{\text{Dekat}}(x) = \begin{cases} 1, & x \leq 20 \\ \frac{35 - x}{35 - 20}, & 20 < x < 35 \\ 0, & x \geq 35 \end{cases}$$

b) Medium Set (Triangular shape [20, 40, 60]):

$$\mu_{\text{Medium}}(x) = \begin{cases} 0, & x \leq 20 \text{ or } x \geq 60 \\ \frac{x - 20}{40 - 20}, & 20 < x \leq 40 \\ \frac{60 - x}{60 - 40}, & 40 < x < 60 \\ 1, & x = 40 \end{cases}$$

c. Far Set (Trapezoidal shape [50, 65, 80, 80]):

$$\mu_{\text{Far}}(x) = \begin{cases} 0, & x \leq 50 \\ \frac{x - 50}{65 - 50}, & 50 < x < 65 \\ 1, & x \geq 65 \end{cases}$$

2) Inferensi Rule Fuzzy

Rule inference uses IF–THEN rules and the AND operator, so the activation value of each rule is obtained using the minimum operator. If several rules produce the same output, the maximum operator is used for aggregation[14]. Defuzzification is performed using the centroid method to obtain a crisp output value that represents the final movement decision[15], as shown in Table I.

TABLE I

EXAMPLES OF FUZZY RULES USED IN THE NAVIGATION SYSTEM

Rule	Left Sensor	Center Sensor	Right Sensor	Output Direction
R1	Close	Close	Close	Turn Left
R2	Close	Close	Medium	Turn Left
R3	Close	Close	Far	Turn Left
R4	Close	Medium	Close	Turn Left
R5	Close	Medium	Medium	Straight

Rule	Left Sensor	Center Sensor	Right Sensor	Output Direction
R6	Close	Medium	Far	Straight
R7	Close	Far	Close	Turn Left
R8	Close	Far	Medium	Straight
R9	Close	Far	Far	Straight
R10	Medium	Close	Close	Turn Left
R11	Medium	Close	Medium	Turn Left
R12	Medium	Close	Far	Turn Left
R13	Medium	Medium	Close	Straight
R14	Medium	Medium	Medium	Straight
R15	Medium	Medium	Far	Straight
R16	Medium	Far	Close	Straight
R17	Medium	Far	Medium	Straight
R18	Medium	Far	Far	Straight
R19	Far	Close	Close	Turn Right
R20	Far	Close	Medium	Turn Right
R21	Far	Close	Far	Turn Right
R22	Far	Medium	Close	Straight
R23	Far	Medium	Medium	Straight
R24	Far	Medium	Far	Straight
R25	Far	Far	Close	Turn Right
R26	Far	Far	Medium	Turn Right
R27	Far	Far	Far	Straight

The rule examples show how the robot chooses a movement direction based on the relative distance condition. When the center sensor reads Near and the right side is Far, the robot turns right because that side provides more open space. When the right sensor reads Near and the left side is Far, the robot turns left. When the three sensors read a balanced Medium condition, the robot moves straight. In very narrow conditions, the robot enters an avoidance or scanning behavior to prevent collision.

3) Defuzzification

Defuzzification converts the fuzzy inference result into a crisp value (crisp output) using the Centroid (Center of Area) method [16][17].

$$z^* = \frac{\int y \cdot \mu_{\text{agg}}(y) dy}{\int \mu_{\text{agg}}(y) dy}$$

4) Numerical Calculation Example:

To demonstrate the mathematical calculations of the fuzzy system, a real-world sensor reading scenario is used as an example:

a) Step 1: Fuzzification

Left sensor ($S_L = 30$ cm):

$$\mu_{\text{Near}}(30) = \frac{35 - 30}{35 - 20} = \frac{5}{15} = 0,333$$

$$\mu_{\text{Sedang}}(30) = \frac{30 - 20}{40 - 20} = \frac{10}{20} = 0,500$$

$$\mu_{\text{Jauh}}(30) = 0$$

Center Sensor ($S_C = 15$ cm)

$$\mu_{\text{Dekat}}(15) = 1,000 \text{ (karena } 15 \leq 20)$$

$$\mu_{\text{Sedang}}(15) = 0$$

$$\mu_{\text{Jauh}}(15) = 0$$

Right Sensor ($S_R = 70$ cm):

$$\mu_{\text{Dekat}}(70) = 0$$

$$\mu_{\text{Sedang}}(70) = 0$$

$$\mu_{\text{Jauh}}(70) = 1,000 \text{ (karena } 70 \geq 65)$$

b) Step 2: Rule Evaluation (Fuzzy Inference)

Rule 3 (R3): IF S_L Near AND S_C Near AND S_R Far THEN Turn Right

$$\alpha_{R3} = \min(0,33; 1; 1)$$

$$\alpha_{R3} = 0,33$$

Rule 6 (R6): IF S_L Medium AND S_C Near AND S_R Far THEN Turn Right

$$\alpha_{R6} = \min(0,5; 1; 1)$$

$$\alpha_{R6} = 0,5$$

c) Step 3 Defuzzification

Since both rules produce a "Turn Right" output, the aggregated output value uses the maximum value:

$$\alpha_{\text{Turn Right}} = \max(0,33; 0,5)$$

$$\alpha_{\text{Turn Right}} = 0,5$$

The centroid calculation is performed by dividing the aggregated output area into several simple geometric shapes (rectangles and triangles). Based on discrete calculations within the 0- 180, a crisp output value is obtained:

$$z^* = 38,45^\circ$$

The value = 38.45 falls within the "Turn Right" set domain (0- 80). This result is sent to the ESP32 microcontroller to instruct the drive motor to steer the robot to the right, thereby avoiding obstacles located in front and to the left.

F. Testing Parameters

The system testing was conducted to evaluate the performance of the ultrasonic sensors, fuzzy logic navigation, robot operating modes, Android application, communication

system, and manual Bluetooth control. The testing types, parameters, and tools used are presented in Table II.

TABLE II.
TESTING PARAMETERS

No	Type of Testing	Parameters Tested
1	Mamdani Fuzzy Logic System	Left, center, and right sensor values, membership degrees, defuzzification values, robot movement direction, and calculation error
2	Automatic and Manual Robot Performance	Test area, testing duration, initial sand mass, collected sand mass, remaining sand mass, and cleaning effectiveness
3	Android Application and Firebase	Registration, login, cleaning start button, brush motors, vacuum motor, battery monitoring, Serial Monitor status, and Firebase status
4	Bluetooth Manual Control	F, B, L, and R command characters, robot movement direction, data reception, and response time

III. RESULTS AND DISCUSSION

A. Mamdani Fuzzy Logic Testing

The Mamdani fuzzy logic system was tested using distance data from the left, center, and right ultrasonic sensors. The sensor values were processed by the fuzzy inference system to determine the robot's movement direction. The test results are presented in Table III.

TABLE III.
MAMDANI FUZZY LOGIC TESTING RESULTS

No.	Left Sensor (cm)	Center Sensor (cm)	Right Sensor (cm)	Calculation	Truning Direction
1	25	70	70	34,50	Right
2	30	15	70	35,80	Right
3	15	40	70	32,07	Right
4	40	40	40	90,00	Straight
5	70	15	15	147,93	Left

The results show that the fuzzy logic system can determine the robot's movement direction based on the distance conditions detected by the three ultrasonic sensors. When the right side has a greater available distance, the robot turns right, while when the left side provides a greater available distance, the robot turns left. When the distances on all three sides are relatively equal, the robot moves straight. These results indicate that the Mamdani fuzzy logic system provides movement decisions according to the detected obstacle conditions.

B. Automatic and Manual Robot Performance

The cleaning performance of the robot was evaluated through ten trials in automatic and manual modes. Cleaning effectiveness was used as the main parameter to compare the robot's performance under both operating conditions.

1) Automatic Control

The automatic mode achieved cleaning effectiveness between 32% and 64%. The highest effectiveness was obtained in the first and second trials at approximately 64%, while the lowest value was approximately 32% in the ninth and tenth trials. The average cleaning effectiveness over the ten trials was approximately 48.8%. The variation in performance was influenced by the autonomous navigation process, in which the robot adjusted its movement based on ultrasonic sensor readings and the fuzzy logic system. Figure 5 shows the cleaning effectiveness obtained from ten trials using the automatic control mode.

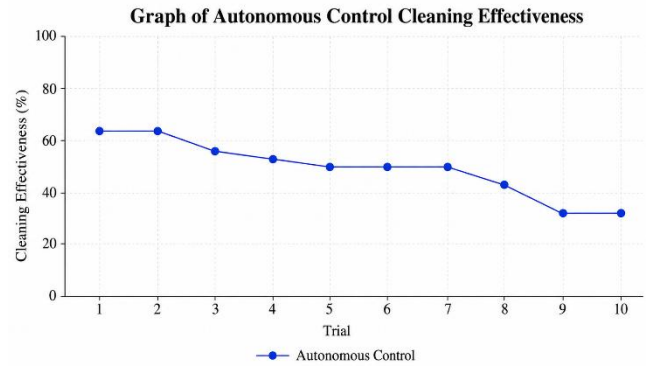


Figure 4. Cleaning effectiveness of automatic control.

2) Manual Control

The manual mode achieved cleaning effectiveness between 70% and 83%. The highest value was approximately 83% in the first three trials, while the lowest value was approximately 70% in the tenth trial. The average cleaning effectiveness was approximately 78.6%. The higher performance was obtained because the operator could directly control the robot's movement toward areas containing more sand. Figure 6 presents the cleaning effectiveness obtained from ten trials using manual control.

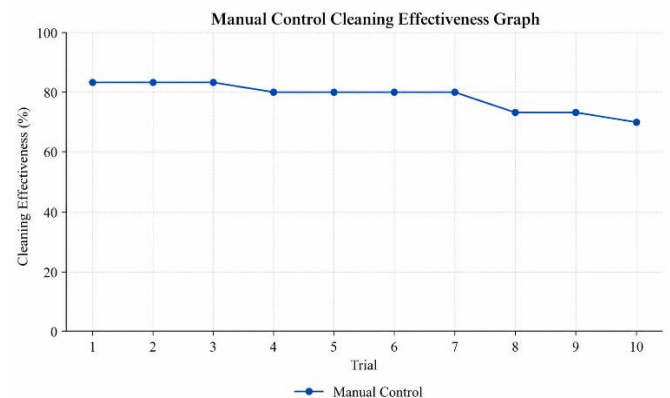


Figure 5. Cleaning effectiveness of manual control.

3) Comparison of Automatic and Manual Control

The comparison shows that the manual mode consistently achieved higher cleaning effectiveness than the automatic mode in all ten trials. The average effectiveness was

approximately 78.6% for manual control, compared with 48.8% for automatic control, resulting in a difference of approximately 29.8 percentage points. This indicates that manual control provided better cleaning performance in the tested conditions, while the automatic mode demonstrated the ability to perform the cleaning process independently using the navigation system. Figure 7. shows the comparison of cleaning effectiveness between automatic and manual control over ten trials.

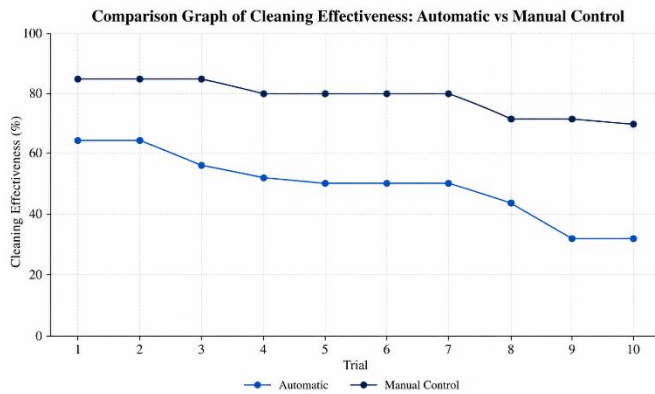


Figure 6. Comparison of cleaning effectiveness between automatic and manual control.

C. Android Application and Firebase

The Android application and Firebase were tested to verify the operation of the robot control and monitoring functions. The tested features included the automatic cleaning button, front brush, vacuum, and battery monitoring. The test results are presented in Table V.

TABLE V.
ANDROID APPLICATION AND FIREBASE TESTING RESULTS

No.	Feature Tested	Expected Result	Serial Monitor	Firebase
1	Start Cleaning	Robot starts automatic movement	Successful	Successful
2	Front Brush	Front brush motor turns ON	Successful	Successful
3	Vacuum	Vacuum turns ON	Successful	Successful
4	Battery Monitoring	Battery percentage displayed in real time	Successful	Successful

The results show that all tested application functions operated as expected. The commands from the Android application were successfully received by the ESP32, while the corresponding status was also successfully updated through Firebase. Battery monitoring was also displayed in real time, indicating that the application can be used for remote control and monitoring of the robot.

D. Bluetooth Manual Control Testing

The Bluetooth manual control was tested to evaluate the robot's response to movement commands transmitted from the Android smartphone to the ESP32. The commands F, B, L, and R were used to control forward, backward, left, and right movements, respectively. The test results are presented in Table IV.

TABLE IV.
BLUETOOTH MANUAL CONTROL TESTING RESULTS

No.	Command	Expected Movement	Expected Movement
1	F	Forward	Successful
2	B	Backward	Successful
3	L	Left	Successful
4	R	Right	Successful

The results show that all Bluetooth commands were successfully received and executed by the ESP32. The robot moved according to the corresponding commands, indicating that the Bluetooth manual control function operated properly.

E. Analysis of Fuzzy-System Success

The success of the fuzzy system in this research can be viewed from two aspects: agreement of defuzzification values and agreement of the robot-direction decisions. In terms of calculation, the manual and MATLAB results were very close. The largest difference in the test data remained below 1%, so the difference did not change the final decision. This indicates that the membership-function equations, rule base, and centroid method were applied consistently.

In terms of implementation, the resulting direction decisions could be displayed through the serial monitor and used as the basis for controlling the robot's movement. The example with left sensor 30 cm, center sensor 15 cm, and right sensor 70 cm produced a Turn Right decision. This decision was consistent with the environmental condition because the right side had more space available to travel than the center of the robot.

The fuzzy system also provides an advantage over fixed-threshold decision making. If only a single distance threshold were used, the robot could produce overly abrupt movement changes when a sensor value was near the threshold. With fuzzy logic, changes in distance values can produce gradual membership degrees, making movement decisions more flexible. This is important for a floor-cleaning robot operating in rooms with varying distances from walls or surrounding objects.

Nevertheless, the fuzzy system in this research remains focused on local directional decision making. This means that the robot's decision is determined by the current sensor conditions rather than a complete room map. The robot can avoid simple obstacles, but it does not yet know which parts of the area have already been cleaned and which parts have not been traversed.

F. Analysis of the Effect of Area Size on Cleaning

The test results show that area size has a direct effect on the robot's cleaning effectiveness. In small areas, the robot has a greater opportunity to pass over the sand during the 1-minute test period. This can be seen in the 60×60 cm and 60×80 cm areas, where automatic mode achieved 63.33% effectiveness. In these areas, the distance that the robot needed to travel was relatively short, so the probability of passing over the dirt was greater.

As the area increased, automatic-mode effectiveness decreased. In the 1.4×1.4 m and 1.4×1.6 m areas, automatic-mode effectiveness reached only 33.33%. This decrease occurred because the testing time remained fixed at 1 minute while the area that needed to be covered became larger. With an unsystematic automatic navigation pattern, the robot did not always pass through all points containing sand.

This condition shows that cleaning effectiveness is not determined only by vacuum power but also by the robot's movement path. If the robot does not pass through an area containing sand, that sand cannot be swept and vacuumed even if the cleaning system is functioning. Therefore, a more orderly cleaning path is needed to improve automatic-mode results.

In manual mode, cleaning effectiveness also decreased as the area increased, but the decrease was not as large as in automatic mode. This was because the user could direct the robot toward areas where sand remained. Thus, the robot passed through dirty areas more often and vacuumed a greater mass of sand. This explains why the average manual-mode effectiveness reached 78.67%, higher than automatic mode.

G. Discussion of IoT System and Manual Control

IoT integration provides convenience in robot operation and monitoring. The Android application is used to activate automatic mode, control the brush and vacuum motors, and monitor the battery. Battery-monitoring data are sent to Firebase so that the user can view power information in real time. This helps users determine the battery condition without opening the robot body or measuring the voltage manually.

Firebase is used because it can store and synchronize data quickly between the application and the microcontroller. In this system, commands from the application are written to the Firebase Realtime Database, after which the ESP32 reads changes in the data and executes commands according to the received values. This mechanism is simple and suitable for an IoT prototype because it does not require a complex local server.

Bluetooth manual control provides an additional function when the user wants to control the robot directly. This mode is useful when the robot needs to be directed to a specific point, such as an area where sand remains, an easily accessible corner, or the initial testing position. The test results show that Bluetooth commands can be responded to in less than 1 second, making manual control sufficiently responsive.

The combination of Firebase and Bluetooth provides two different communication paths. Firebase is suitable for monitoring and internet-based commands, while Bluetooth is suitable for short-range local control. Using both

communication systems makes the robot more flexible because the user can still operate the robot manually even when internet-based control is not used.

H. System Limitations

The robot developed in this research still has several limitations. First, the robot is designed only for flat indoor floors. It has not been tested on carpeted surfaces, stairs, wet surfaces, or floors with differences in height. This limitation is important because the wheel shape, brush position, and vacuum capability of the prototype were not designed for more difficult surface conditions.

Second, the navigation system uses only ultrasonic sensors. Ultrasonic sensors have advantages in terms of cost and ease of use, but they have limitations when detecting objects with inclined surfaces, uneven surfaces, or materials that reflect ultrasonic waves poorly. Under certain conditions, sensor readings may become unstable, requiring filtering or additional sensors.

Third, the robot does not yet have a room-mapping system. Without mapping, the robot cannot determine its position in the room or which areas have already been cleaned. As a result, the robot may pass through certain areas more than once while other areas remain untouched. This is one of the causes of lower automatic-mode effectiveness compared with manual mode.

Fourth, the cleaning system is still limited to dry dirt such as sand and small particles. The robot is not designed to vacuum liquids, oily dirt, or dirt that is strongly attached to the floor. Therefore, the test results in this research apply only to dry-dirt conditions according to the defined scenario.

I. Development Recommendations

Future development can include adding a LiDAR sensor. LiDAR can provide more detailed distance information and a wider observation range than ultrasonic sensors. With this information, the robot can recognize open space and obstacles more effectively, allowing its movement to be made more directed and reducing the risk of collisions.

In addition to LiDAR, the robot can be equipped with a coverage path planning algorithm. This algorithm is needed so that the robot not only avoids obstacles but can also arrange a more evenly distributed cleaning path. For example, the robot can move in row or grid patterns so that the entire area has a greater chance of being traversed during cleaning.

Mechanical improvements are also needed in the brush and vacuum sections. The brush width can be adjusted to direct dirt toward the suction channel more effectively. The vacuum position and airflow channel can also be improved to reduce air leakage and increase suction power in areas close to the floor.

On the application side, the system can be developed by adding test history, cleaning duration, mode status, and battery-usage graphs. These data can help users evaluate robot performance over time. In addition, historical data can be used to analyze the relationship among battery power, operating time, and cleaning effectiveness.

Further testing should be conducted with a larger number of trials and more varied types of dirt. In addition to sand, testing could use fine dust, small crumbs, or mixtures of dry dirt. Such variation would provide a more complete understanding of the robot's ability to handle more realistic cleaning conditions.

IV. CONCLUSION

The floor cleaning robot based on the Mamdani Fuzzy Logic method was successfully developed and tested. The Mamdani Fuzzy Logic system successfully processed distance information from the left, center, and right ultrasonic sensors to determine the robot's movement direction, with an average calculation error of 0.51% compared with the MATLAB simulation. The robot was also able to perform cleaning in both automatic and manual modes, with average cleaning effectiveness of 49.67% and 78.67%, respectively, resulting in a difference of 30.00%. The Android application and Firebase successfully supported registration, login, cleaning activation, cleaning component control, and battery monitoring. In addition, the Bluetooth manual control successfully received and executed the F, B, L, and R commands for forward, backward, left, and right movements. Overall, the developed system successfully performed automatic navigation, floor cleaning, application-based monitoring, and manual control according to the designed functions.

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