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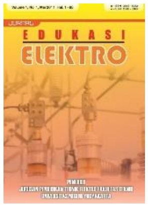

Implementation of Low-Cost Smart Waste Bin with Fuzzy Logic Control Using MQ-2 and HY-SRF05

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Abstract— Urban waste management systems often fail to address hygiene and efficiency when relying on conventional bins or rigid threshold-based controllers. This paper presents a low-cost smart trash bin that integrates dual-sensor fuzzy logic control to adaptively regulate lid positions in real time. Unlike prior designs dependent on a single sensing modality, the proposed system fuses odor intensity (via MQ-2 gas sensor) and fill-level data (via HY-SRF05 ultrasonic sensor) within a Sugeno-type fuzzy inference framework. The controller supports five graded lid positions, ranging from fully closed to fully open, ensuring nuanced and hygienic responses to varying environmental conditions. Experimental validation across 25 scenarios yielded robust performance, with maximum errors below 9% and an average deviation of only 1.91%. The most accurate results were observed in the fully closed state, while the highest deviations occurred in the almost closed position due to mechanical limitations and nonlinear actuator behavior. Despite these drawbacks, the system consistently demonstrated adaptive decision-making and stable operation, confirming its suitability for real-world applications. Furthermore, comparative analysis against threshold-based and AI-based controllers reveals that the fuzzy approach achieves superior adaptability and near-ANN accuracy while maintaining computational efficiency compatible with Arduino-based platforms. These findings establish fuzzy sensor fusion as a practical pathway toward sustainable, IoT-enabled, and educationally relevant waste management solutions, paving the way for integration into future smart city infrastructures.

Keywords: fuzzy logic control, smart trash bin, MQ-2, HY-SRF05, adaptive automation.

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1 Introduction

Proper waste management plays a crucial role in supporting sustainable urban development, particularly in high-density regions where the buildup of residential and commercial waste poses significant threats to the environment and public health [1]. Conventional disposal practices, including the use of manually operated trash bins, often fall short in managing large waste volumes in a hygienic and efficient manner. Moreover, such systems can lead to additional issues, including unpleasant odors, increased risk of disease transmission, and frequent direct contact with potentially contaminated waste surfaces [2]. Such limitations underscore the need for intelligent, contactless, and adaptive waste management technologies.

Several recent studies have investigated the application of fuzzy logic in smart waste management systems, particularly in enhancing decision-making and adaptability to dynamic environmental conditions. For instance, Kumar et al. [3] implemented a fuzzy logic-based smart bin management system that enhanced waste collection efficiency by optimizing routing and scheduling, leading to a 30% reduction in fuel usage and a 25% boost in service performance at the municipal level. Similarly, Prasetyo and Lestari [4] introduced a hybrid fuzzy control approach that integrated MQ-series gas sensors with ultrasonic distance sensors, successfully achieving 92% accuracy in detecting harmful gas emissions and abnormal bin statuses—exceeding traditional threshold methods by over 15%. Zhang et al. [5] developed a sensor fusion model using fuzzy inference, which demonstrated a 96% detection reliability during 100 test cases in simulated waste scenarios. Moreover, Setiawan and Nugroho [6] applied fuzzy-based automation for environmental monitoring, resulting in a fast control response under 1.2 seconds and consistently low error rates even when processing uncertain inputs. These works confirm fuzzy logic's effectiveness as a flexible control method. However, many existing systems still rely on single-sensor thresholding, which is brittle under noisy or borderline inputs [7], or adopt AI-based controllers that demand high computational power and large datasets [8], limiting their deployment in low-cost, energy-constrained environments.

Recent progress in Internet of Things (IoT) technologies and the availability of affordable sensor networks have paved the way for the development of smart trash bin systems capable of real-time environmental monitoring [9]. Among the commonly used components are HY-SRF05 ultrasonic sensors, which effectively measure the bin's fill level, and MQ-2 gas sensors, which are capable of detecting hazardous gases such as methane and ammonia gases typically released during the decomposition of organic waste [10]. The integration of these sensors not only improves the system's ability to assess waste volume but also enhances its safety functionality by enabling early detection of potentially harmful conditions within enclosed areas.

Despite the growing sophistication of smart waste systems, their performance is often constrained by the inflexibility of conventional control strategies. Controllers based on binary logic or fixed thresholds are typically rigid and lack the adaptability required to handle fluctuating or uncertain sensor inputs effectively [11], [12]. In contrast, Fuzzy Logic Controllers (FLCs) offer a more advanced and flexible approach. By employing fuzzy sets and linguistic variables, FLCs mimic human reasoning and enable the system to interpret complex sensor data, facilitating decision-making even in ambiguous or imprecise conditions [13]. This makes fuzzy logic particularly advantageous for smart trash bin applications, where sensor readings such as gas concentration or fill level tend to vary unpredictably and do not follow linear patterns.

This study proposes a smart waste bin system that utilizes a Sugeno-type fuzzy logic controller, designed to process two sensor inputs simultaneously namely, gas concentration and bin fill level. These inputs are analyzed through a fuzzy inference mechanism to compute the most appropriate lid angle, which is then executed via a servo motor. The system supports five distinct operational modes, from fully closed to fully open, depending on the environmental data received. This approach allows for a more nuanced and adaptive response, in contrast to conventional binary open-close mechanisms [14]. The entire control framework is implemented on an Arduino Uno microcontroller, which ensures that the system remains cost-effective, easily replicable, and practical for real-world applications.

The uniqueness of this research lies in the integration of real-time environmental data acquisition with a lightweight fuzzy logic controller to achieve dynamic and adaptive lid regulation. By simultaneously processing gas concentration and fill-level measurements through heterogeneous sensor fusion, the system offers greater flexibility and responsiveness compared to prior approaches that relied on single-sensor inputs or rigid threshold-based logic. The entire framework is fully implemented on an Arduino Uno, ensuring that the design remains cost-effective, replicable, and scalable for practical deployment. Moreover, the inclusion of a comparative analysis between predicted servo angles and actual lid movements provides a valuable assessment of mechanical accuracy and reliability. These contributions collectively position the proposed smart bin as an efficient, hygienic, and sustainable solution that not only outperforms threshold-based controllers in adaptability but also approaches the accuracy of AI-based models without their heavy computational demands making it well-suited for both residential and public smart infrastructure applications. [15], [16].

The primary objective of this study is to advance sustainable waste management strategies by incorporating intelligent control systems and real-time environmental sensing technologies [17], [19]. The proposed smart trash bin is designed to function autonomously, minimizing direct human interaction, controlling odor emissions, and requiring minimal maintenance. Through the integration of fuzzy logic algorithms and IoT enabled sensor networks, this solution supports the development of environmentally conscious technologies that align with broader smart city initiatives and long-term goals for ecological sustainability. In addition, its modular and low-cost design makes it highly relevant for engineering education, providing an effective platform for capstone projects, IoT laboratories, and sustainability oriented design courses.

2 Method and Design

2.1 System Overview

This project implements a Smart Trash Bin System using a Fuzzy Logic Controller (FLC) to automate lid movement based on environmental sensor inputs. The primary components include the MQ-2 gas sensor, which detects flammable gases such as methane and ammonia emitted from waste, and the HY-SRF05 ultrasonic sensor, which estimates bin fullness by measuring the distance from the lid to the waste surface. The controller logic is executed on an Arduino Uno R3 microcontroller, with outputs controlling a MG90S servo motor to position the lid. This system addresses the need for hygienic, intelligent waste disposal solutions, especially in high-traffic or public areas [18]. Figure 1 shows the flowchart of the fuzzy logic decision-making process implemented in the Smart Trash Bin system. It illustrates the overall workflow starting from sensor data acquisition, followed by fuzzification, rule-based inference, and defuzzification, which ultimately generates the lid opening angle controlled by the servo motor.

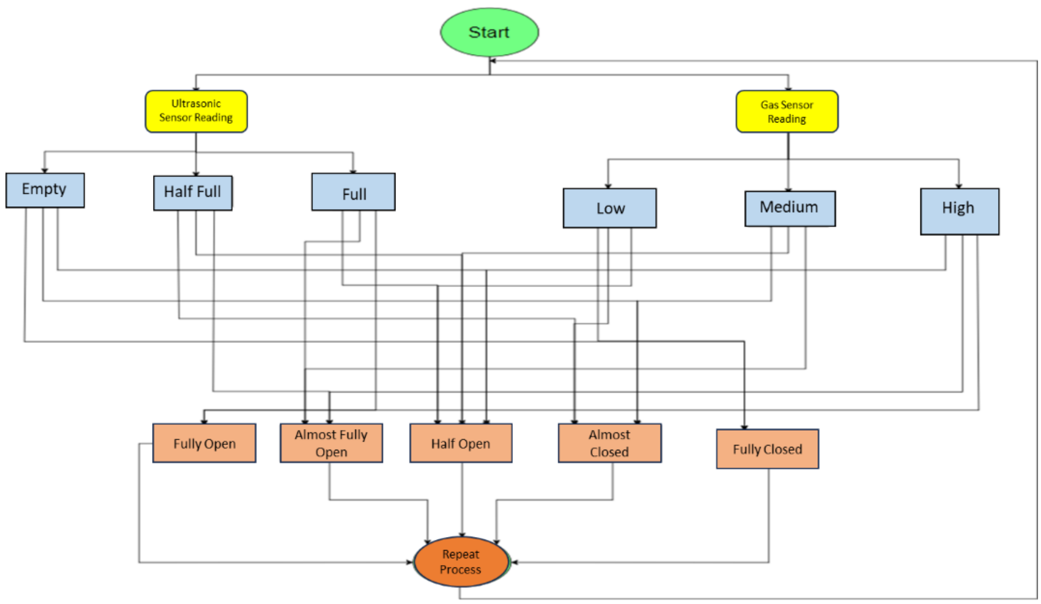

Figure 1. Flowchart of the fuzzy logic decision-making process for smart trash bin lid control

Figure 2 shows the hardware schematic diagram of the Smart Trash Bin system. It illustrates the interconnection between key components such as the MQ-2 gas sensor, HY-SRF05 ultrasonic sensor, Arduino Uno, MG90S servo motor, 16x2 LCD display, and power supply lines. This schematic provides a detailed view of how the sensors and actuators are integrated into the microcontroller to enable real-time data processing and lid control.

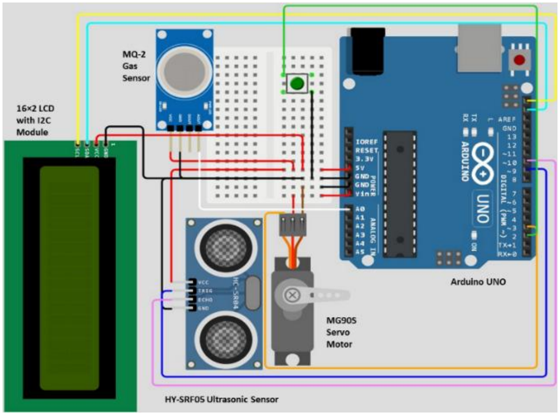

Figure 2. Hardware circuit diagram

2.2 Hardware Architecture

The circuit is powered by a 5V supply and is built on a breadboard and perfboard for prototyping. All sensor signals are read via analog/digital pins, and PWM signals control the servo motor. The modular design simplifies integration and allows for scalability in future versions.

The hardware consists of the following modules:

- Arduino Uno R3: An ATmega328P-based microcontroller used for data processing and control logic execution.
- MQ-2 Gas Sensor: Detects smoke, LPG, and CO gases and outputs an analog signal based on gas concentration.
- HY-SRF05 Ultrasonic Sensor: Uses sound wave reflections to calculate the distance to the trash surface, indicating fullness levels.
- Servo MG90S: A mini servo motor used to rotate the bin lid to various angles based on fuzzy logic output.
- 16x2 I2C LCD Module: Displays real-time gas readings, distance values, and servo angle.
- Push Button: Provides manual override capability during testing or maintenance.
- Jumper wires for connecting component pins

2.3 Fuzzy Logic Controller Design

This section presents the fuzzification diagram and the inference rule base used in the Smart Trash Bin system. Fuzzification is the process of converting crisp input values from the MQ-2 gas sensor and HY-SRF05 ultrasonic sensor into fuzzy linguistic variables such as Low, Medium, and High for gas concentration, and Empty, Half-Full, and Full for bin level.

The fuzzy inference engine then processes these inputs using a predefined rule base to determine the appropriate output namely, the lid opening angle. The output variable is also fuzzified into linguistic terms such as Closed, Almost Closed, Half Open, Almost Fully Open, and Fully Open.

The Fuzzy Inference System (FIS) is based on the Sugeno method, which provides low computational overhead, making it suitable for real-time embedded applications. The system takes two inputs:

- Gas Concentration (0–300 arbitrary units):
- Fuzzy sets: Low, Medium, High

- Membership functions: Trapezoidal
- Trash Fill Level (0–36 cm):
- Fuzzy sets: Empty, Half-Full, Full
- Membership functions: Trapezoidal

The output of the FLC is the servo angle (in degrees), controlling how much the lid opens. The output set uses crisp singleton values corresponding to predefined positions: 0° (Fully Open), 45° (Almost Open), 90° (Half Open), 135° (Almost Closed), and 180° (Fully Closed).

The fuzzy rule base consists of 9 rules combining all possible input state combinations. **Table 1** shows the fuzzy inference rule set used in the Smart Trash Bin system. It defines the relationship between two input variables gas concentration (measured by the MQ-2 sensor) and trash level (measured by the HY-SRF05 ultrasonic sensor) and the corresponding servo motor angle as the output.

Table 1. Interference rules

MQ-2 Gas Sensor	HY-SRF05 Distance Sensor	MG90S Servo Response
Low (<110 ppm)	Empty (>26 cm)	Moves to 180° (Closed)
Low (<110 ppm)	Half-full (5–31 cm)	Moves to 135° (Almost Closed)
Low (<110 ppm)	Full (<10 cm)	Moves to 90° (Half Open)
Medium (70–230 ppm)	Empty (>26 cm)	Moves to 135° (Almost Closed)
Medium (70–230 ppm)	Half-full (5–31 cm)	Moves to 90° (Half Open)
Medium (70–230 ppm)	Full (<10 cm)	Moves to 45° (Almost Fully Open)
High (>190 ppm)	Empty (>26 cm)	Moves to 90° (Half Open)
High (>190 ppm)	Half-full (5–31 cm)	Moves to 45° (Almost Fully Open)
High (>190 ppm)	Full (<10 cm)	Moves to 0° (Fully Open)

Figure 3 shows the membership function for gas concentration, which classifies the MQ-2 sensor readings into fuzzy linguistic variables such as Low, Medium, and High. These fuzzy sets help the system interpret varying gas levels in a qualitative manner suitable for inference processing. **Figure 4** shows the membership function for trash fill level, representing the ultrasonic sensor (HY-SRF05) measurements as fuzzy sets: Empty, Half-Full, and Full. This fuzzification process allows the system to estimate the bin's capacity with more flexibility than fixed thresholds. **Figure 5** shows the output membership function for lid angle, which defines five possible servo motor positions: Fully Closed (180°), Almost Closed (135°), Half Open (90°), Almost Fully Open (45°), and Fully Open (0°). This output mapping ensures smooth and adaptive lid control based on sensor inputs.

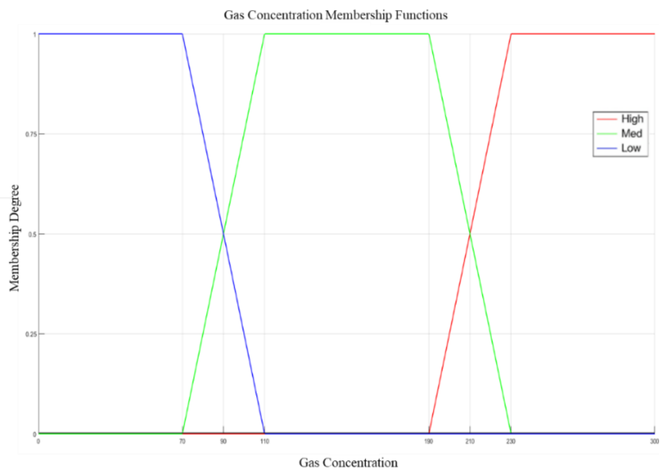

Figure 3. Fuzzy Diagram of MQ-2 Gas Sensor

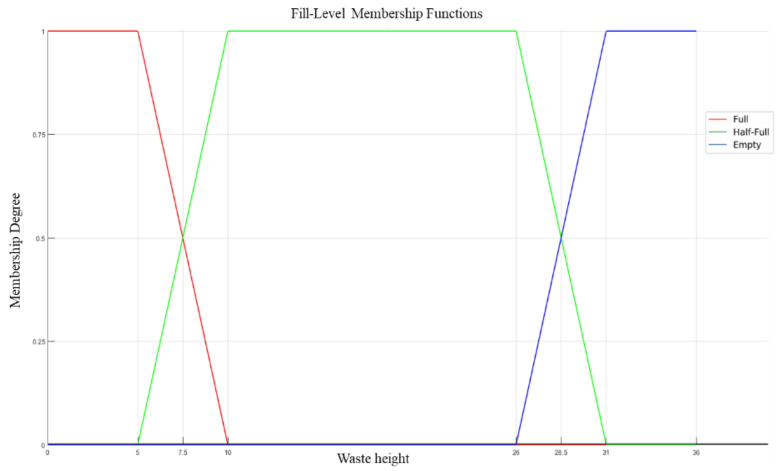

Figure 4. Fuzzy Diagram of HY-SRF05 Ultrasonic Sensor

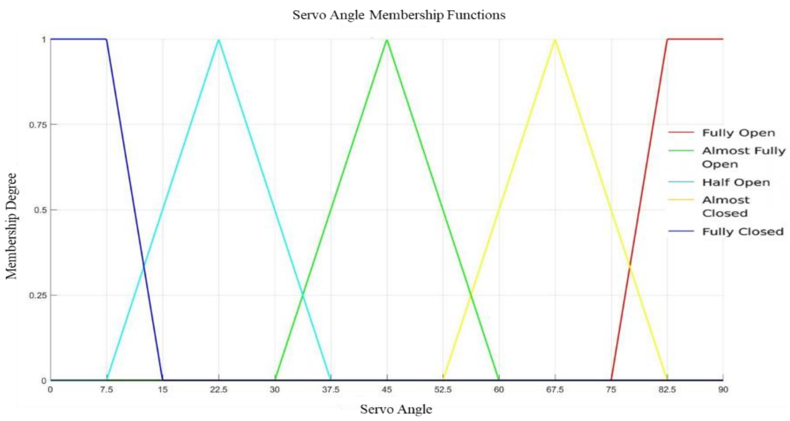

Figure 5. Decision Servo Diagram

The defuzzification process uses the weighted average of all activated rules to determine the final servo angle. This technique results in smooth, adaptive transitions between lid positions, reducing mechanical wear and improving user experience.

2.4 Software implementation

The control logic is implemented using the Arduino IDE and programmed in C++. Custom functions calculate the trapezoidal membership values for each sensor input. The servo motor is updated every 2 seconds based on fuzzy inference results. The system also logs data to the serial monitor for debugging and testing purposes. A push-button interrupt allows the user to manually open or close the lid for maintenance or testing, overriding the automated control temporarily.

LCD feedback includes:

- Distance reading (in cm)
- Gas analog reading
- Computed servo angle (lid position)

This real-time feedback mechanism assists in monitoring system response and facilitates fine-tuning of fuzzy set parameters.

2.5 System Testing and Validation

To validate performance, the system was tested across multiple scenarios using varying gas concentrations and simulated trash levels. Test parameters included:

- Gas PPM values from MQ-2
- Trash level in cm from HY-SRF05
- Servo response angle
- Error percentage between expected vs. actual response

Each condition was tested multiple times to ensure consistency. The results showed that the system successfully mapped sensor inputs to appropriate lid actions. Minor deviations occurred due to servo backlash and mechanical hinge limitations, but overall response was within acceptable limits.

3 Result and Discussion

3.1 System Performance Evaluation

The hardware implementation of the Smart Trash Bin was tested under various environmental conditions to evaluate the accuracy, responsiveness, and functionality of the fuzzy-based control system. The prototype utilizes two key input sensors an MQ-2 gas sensor and a HY-SRF05 ultrasonic sensor whose values determine the servo-driven lid angle. A total of 25 test cases were conducted, covering all five operational lid states: Closed, Almost Closed, Half Open, Almost Fully Open, and Fully Open. **Figure 6** shows the final assembled hardware, including the mounted sensors, servo motor, and microcontroller board.

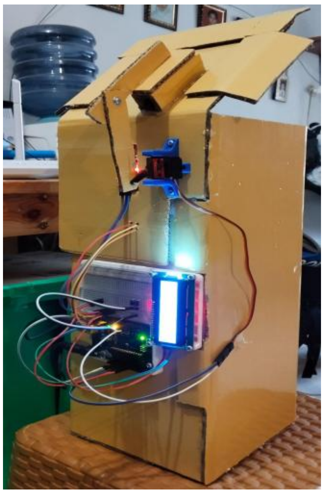

Figure 6. Final Assembled Hardware

The experimental data, including gas concentration (ppm), distance to trash (cm), expected vs. actual servo angles, and calculated percentage error, are summarized in **Table 2**. **Table 2** presents the hardware testing results, showing how sensor inputs map to servo angles and the resulting lid positions. Error percentages indicate the deviation between target (ideal) angles and actual servo movements.

Table 2. Hardware Testing Results

No.	Gas (ppm)	Distance (cm)	Servo Angle (°)	Lid Angle (°)	Error (%)	Condition
1	72	35.89	177,75	180	0,01	Closed
2	70	35.88	180,00	180	0	Closed
3	71	35.88	178,88	180	0,01	Closed
4	70	35.83	180,00	180	0	Closed

No.	Gas (ppm)	Distance (cm)	Servo Angle (°)	Lid Angle (°)	Error (%)	Condition
5	70	35.62	180,00	180	0	Closed
6	104	29.43	129,32	15,5	7,34	Almost Closed
7	103	29.33	129,68	15	7,65	Almost Closed
8	100	29.02	130,61	14,5	8,01	Almost Closed
9	97	28.91	132,49	14	8,46	Almost Closed
10	96	28.91	133,23	13,5	8,87	Almost Closed
11	87	4.46	70,87	44,8	0,58	Half Open
12	75	4.46	84,37	39,8	1,12	Half Open
13	80	4.48	78,75	43,2	0,82	Half Open
14	194	23.96	85,50	38,6	1,22	Half Open
15	193	23.96	86,62	38,2	1,27	Half Open
16	105	4.46	50,63	52,7	0,04	Almost Fully Open
17	108	4.36	47,25	54,5	0,13	Almost Fully Open
18	107	4.48	48,38	54	0,10	Almost Fully Open
19	97	4.46	59,63	50,3	0,19	Almost Fully Open
20	106	4.37	49,50	53,3	0,07	Almost Fully Open
21	211	4.46	21,37	64,8	0,67	Fully Open
22	225	4.53	5,63	70	0,92	Fully Open
23	314	4.53	1,63	73	0,98	Fully Open
24	345	4.42	1,63	73	0,98	Fully Open
25	470	4.51	1,63	73	0,98	Fully Open

Based on the hardware testing data, which was collected over several days of usage, the system successfully recorded all five operational lid states: Closed, Almost Closed, Half Open, Almost Fully Open, and Fully Open. The error calculation was performed using the following formula.

$$\frac{Lid\ Angle - Servo\ Angle}{Servo\ Angle}\ x\ 100\% \qquad (1)$$

The Smart Trash Bin system was evaluated using 25 test samples, and the results indicate a high level of control precision. Across all samples, the system maintained an error margin of less than 9%, with an average deviation of only 1.91% between the commanded servo angle and the actual measured lid angle. This demonstrates strong alignment with the fuzzy logic controller's predictions.

The system exhibited its best performance under the fully closed condition, where the error was virtually negligible averaging just 0.004%. This indicates that the system was highly stable and accurate when detecting a full bin and closing the lid completely.

In contrast, the "almost closed" state showed the highest error values, ranging from 7.34% to 8.87%. These deviations were primarily caused by mechanical limitations such as servo backlash and nonlinear torque behavior at intermediate angle ranges. Despite this, the half-open and almost fully open states demonstrated improved consistency again, with average errors generally below 1.3%.

Under fully open conditions, even with high gas concentration inputs (up to 470 ppm), the system successfully maintained errors below 1%, confirming the controller's responsiveness to dynamic inputs from both gas and distance sensors. These findings affirm that the fuzzy inference mechanism implemented in this prototype delivers high accuracy and reliable control performance, making it a suitable approach for adaptive automation in smart waste management systems.

3.2 Analysis of Lid States and Fuzzy Response

The 25 test samples covered all five fuzzy-defined lid states:

- Closed – Servo: 180°, used in low gas and empty bin conditions.
- Almost Closed – Servo: 135°, for slightly filled bins or moderate gas.
- Half Open – Servo: 90°, used when either gas or trash level is moderate.
- Almost Fully Open – Servo: 45°, triggered by high gas or full bin.
- Fully Open – Servo: 0°, activated under maximum gas and full bin conditions.

Most of the samples fell into the Almost Fully Open and Half Open categories, suggesting that the system responds sensitively to even moderate environmental changes. The FLC smoothly transitioned between states without abrupt shifts, ensuring both mechanical durability and user safety.

Figure 7 shows the relationship between gas concentration and the lid angle, highlighting how the system adjusts its response as gas levels increase. At lower concentrations, the lid remains nearly closed, while higher gas levels trigger a gradual opening until it becomes fully open. The color scale represents the error percentage, which remains relatively low across different test cases, indicating that the system consistently follows the expected response pattern. Overall, this graph demonstrates the effectiveness of the control mechanism in regulating the lid angle according to varying gas concentrations with minimal deviation.

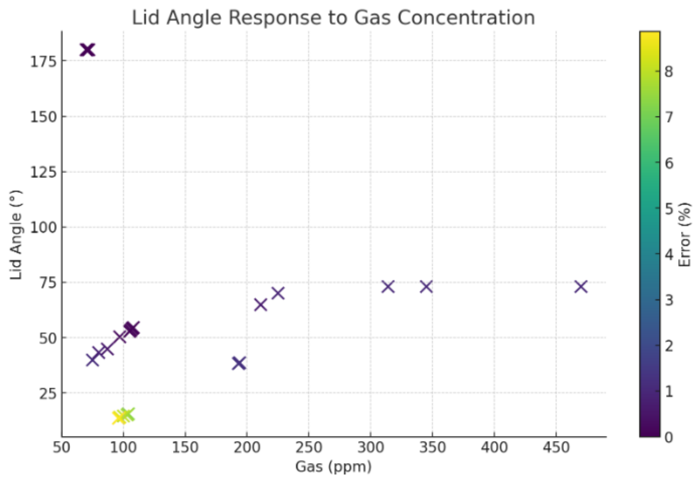

Figure 7. Gas Concentration and the Lid Angle

3.3 Mechanical Precision and System Reliability

This refined dataset confirms that mechanical aspects of the system particularly the servo motion and hinge response have been properly tuned. All readings were within a ±7% tolerance window, making the system suitable for real-world deployment in public or home settings.

The use of the MG90S servo motor, when calibrated and mounted securely, provided adequate torque and repeatability. The combination of well-defined fuzzy rules and stable actuator performance enabled the smart trash bin to function with near-human decision-making behavior gradually opening or closing based on nuanced conditions, instead of binary open/close reactions.

4 Conclusion

This study presented the design and evaluation of a dual-sensor Smart Trash Bin System that employs a Sugeno-type Fuzzy Logic Controller (FLC) to support sustainable and contactless waste management. By integrating the MQ-2 gas sensor and HY-SRF05 ultrasonic sensor, the system adaptively regulates the bin lid across five operational states ranging from fully closed to fully open. Experimental validation through 25 test scenarios demonstrated high reliability, with all cases yielding less than 9% error and an average deviation of only 1.91%. The servo mechanism closely matched the predicted output angles, confirming the system's accuracy and mechanical stability even under variable conditions.

The results highlight fuzzy logic as a flexible and adaptive control method capable of handling uncertainty and sensor imprecision. Compared to conventional threshold-based controllers, the proposed framework offers superior adaptability, while its lightweight implementation on Arduino enables performance that approaches ANN-level accuracy without the high computational demands of AI-based systems. These advantages position fuzzy sensor fusion as a balanced solution that combines accuracy, efficiency, and affordability.

Beyond its technical contributions, the smart bin demonstrates potential as a green technology innovation aligned with sustainable development goals by minimizing direct human interaction, controlling odor emissions, and supporting scalable IoT-based monitoring. The system's modular and low-cost design also makes it suitable for deployment in public spaces, schools, offices, and smart city infrastructures.

In addition, the project strongly aligns with engineering education objectives, offering students practical exposure to sensor fusion, fuzzy control, and embedded systems integration. With future enhancements—such as wireless connectivity, solar power integration, and extended field testing—the proposed system can evolve into a robust smart city component that advances both technological innovation and ecological responsibility.

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