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Design Control and Monitoring System using the Fuzzy Mamdani Method on IoT-Based Air Conditioner

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Abstract

The development of Air Conditioner technology to stabilize the temperature and humidity of the air in a room has affected human life activities. This research designed an automatic control system for air conditioning using the Fuzzy Mamdani method, because it is known that air conditioners have the largest cost burden compared to other electronic devices. Then, this research designed a control system consisting of a DHT22 Sensor as an input to detect the room temperature controlled by the ESP32. Furthermore, the results of data collection are analyzed using the Fuzzy Mamdani method so that the defuzzification output instructs the relay to take action, namely switching off to adjust the temperature degree and display data to the IoT platform, ThingSpeak. The results of this research show that the DHT22 sensor test was successfully calibrated with a hygrometer comparator with an error value of 0.4%. Then, the prototype design based on fuzzy rules has been successfully implemented with an error value of 9.2% from the manual comparison so that it is concluded that the deviation difference is still recommended. This indicates that the system effectively maintains desired environmental conditions while improving energy efficiency by reducing unnecessary AC usage. The results confirm the feasibility of implementing IoT-based fuzzy control systems for practical energy-saving applications.

Keywords: Air Conditioner, Control system, DHT22, ESP32, Fuzzy Mamdani, Software Simulation.

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1. Introduction

Currently, human needs for technology [1]–[3] are growing which affects human life so that it facilitates the running of activities. The example is Air Conditioners (AC) was used in almost all places, for example, commercial and residential buildings which account for about 60% of electricity consumption.

An air conditioner is a machine [4] that is made to stabilize the temperature and humidity of the air in a room. This research was conducted in one of the office rooms, which often uses AC for a long time. Therefore, it also has an impact on the electrical energy used so it is necessary to monitor its use. The emphasis on improving energy efficiency and air conditioning innovation aims to reduce operating costs [5]. A significant amount of electricity is consumed due to the excessive use of ACs in various activities within a room. This is mainly due to inefficient usage and the tendency to forget to turn them off when not needed. Therefore, implementing a control mechanism for AC is essential to prevent energy waste.

Fuzzy logic control [6]–[8] was selected for this research due to its capability to process vague and imprecise data, making it suitable for non-linear systems such as environmental control. Unlike conventional binary logic systems, fuzzy logic mimics human reasoning by applying degrees of truth. This approach allows more adaptive and responsive control strategies when environmental factors like temperature and humidity fluctuate. Moreover, the use of fuzzy control [6]–[8] provides flexibility in rule configuration, making it ideal for integration with Internet of Things (IoT) platforms where real-time adjustments are crucial. The proposed control tool also offers advantages in terms of energy efficiency, cost-effectiveness, and automation of AC operations, improving environmental comfort while minimizing energy waste.

In this study, we designed the AC control system using Arduino [9]–[11] and used the Fuzzy Mamdani [6]–[8] method to conduct IoT-based monitoring. to support the design, programming, and implementation of research, we review the Fuzzy Mamdani methods [6]–[8], DHT22 sensors, IoT [12]–[14], and the ThingSpeak monitoring system [15]. Furthermore, the design of room temperature monitoring system and room temperature testing using an IoT system-based microcontroller were implemented. The room temperature testing data and their analysis show the effectiveness of AC control.

2. Research Method

2.1 Literature Review

The system employs a DHT22 sensor to detect room temperature and humidity..It operates with a relative humidity range of 0–100%. DHT22 has been used in IoT-BC. [16] This sensor provides a calibrated digital signal output. This sensor has a temperature accuracy of 0.5ºC and a humidity accuracy of 2% RH. DHT22 resolution is about 0.1% RH and 0.1ºC. Power voltage should be 3.3-5.5V [17]. The working principle of DHT22 is through the built-in capacitive humidity sensor and thermistor to measure [18].

Then the data sensor is processed using the Fuzzy Mamdani method [19]–[21]. Fuzzy Logic (FL) allows the mathematical translation of linguistic variables into numerical form [22]. This method used because this method satisfies the specifications of the most extensive fuzzy model [23]. Each input/output control FL must be expressed in fuzzy set notation using linguistic forms. The result of the rule evaluation is a fuzzy result for each type of consequence action. The final stage is defuzzification, where fuzzy quantities are converted into crisp quantities [8], [24], [25]. Then ESP32 as a microcontroller, function as the control center of the design. The ESP32 microcontroller has a powerful chip with dual processing cores. This makes it faster than the other controllers discussed above [26]–[28], operates 32-bit programs and has clock frequencies that can reach up to 240MHz and has 512 Kb of RAM [29], then comes with built-in Bluetooth and Wi-Fi features [30] so that it can be integrated with IoT.

When the sensor and time work, the relay will work as an output according to fuzzy rules that have been programmed on the microcontroller. The relay uses an electromagnet to operate the contactor to the On/Off [31] AC indicator. In the circuit functions as a protector, disconnected or off when overcurrent occurs [32] The relay used is a 1 channel model relay. This relay operates with a voltage of 5V. The NO on relay is connected to each indicator, while the COM relay is connected to a power source [33].

Then the data will be connected to IoT. IoT platforms offer flexibility to choose the type of communication technology, according to the needs of the application [34]. The MQTT protocol in IoT displays message transmission in both directions between client-server [35]. The IoT used is ThingSpeak which is a platform service that can hold all input data collected using the KEYS API. Sensors and actuators connect to the ThingSpeak cloud platform using signal conditioning circuitry and Wi-Fi chips to upload sensor readings [36]. Data information recorded every 15 seconds will then be displayed on the website so that we can monitor the room temperature parameters in real-time.

2.2 Design

This research was designed in software simulation using the Fuzzy Mamdani method. The design of the tool uses ESP32, DHT22 Sensor, and relay. Then, the software design uses an Arduino IDE which is integrated with the ESP32 using a USB to serial cable. Furthermore, it is connected to ThingSpeak so that it can be monitored based on IoT, as shown in Figure 1.

Figure 2 shows the design of a system diagram block consisting of a DHT22 sensor to detect room temperature and then processed by ESP32 using the Fuzzy Mamdani method. When the sensor and time are working, the relay will run according to Fuzzy rules that have been programmed on the microcontroller. Then the data is connected to the IoT platform, ThingSpeak, to display the monitoring results in real-time.

2.1 Fuzzy Mamdani

Fuzzification consists of a set of formations of Fuzzy sets. Table 1 displays the degree of temperature membership, which is mapped into several conditions including cold (range 0ºC-15ºC), cool (range 8^0C-20ºC), normal (range 15º C-25ºC), warm (range 20ºC-30ºC), and hot (range 25ºC-35ºC).

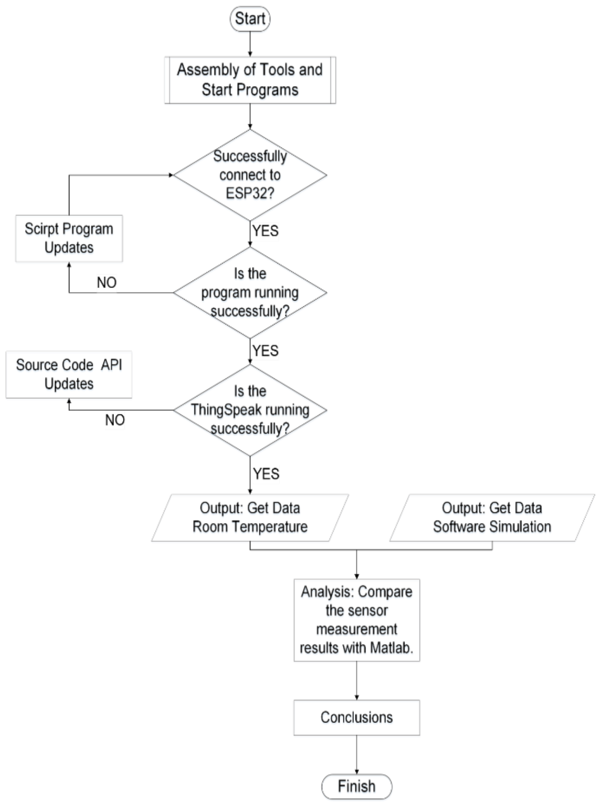

Fig. 1. Flowchart system

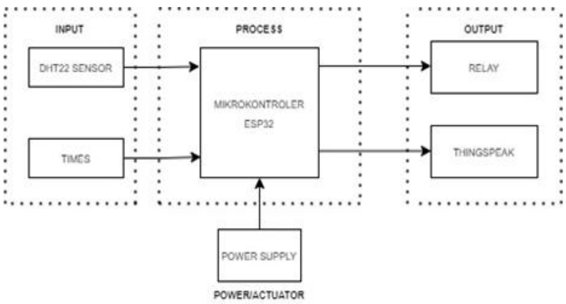

Fig. 2. Block diagram

2.1 Fuzzy Mamdani

Table 2 represents the degree of time membership, which is mapped into several conditions which is divided into the following as midnight (range 00.00-08.00), morning (range 04.00-12.00), afternoon (range 08.00-16.00), evening (range 12.00-20.00), night (range 16.00-24.00). This table illustrates the variation in room temperature throughout the day.

Table 1. Temperature Membership degree

No	Condition	Membership Degree (^{0}C)
1	Cold	0, 8, 15
2	Cool	8, 15, 20
3	Normal	15, 20, 25
4	Warm	20, 25, 30
5	Hot	25, 30, 35

Table 2. Time Membership Degree

No	Condition	Membership Degree (Hours)
1	Midnight	0, 4, 8
2	Morning	4, 8, 12
3	Afternoon	8, 12, 16
4	Evening	12, 16, 20
5	Night	16, 20, 24

Table 3 represents the degree of relay membership resulting in Relay OFF, 1st Relay ON, 2nd Relay ON, 3rd Relay ON.

Table 3. Relay Membership Degree

No	Condition	Membership Degree
1	Relay OFF	0, 0, 0
2	1st Relay ON	0, 8, 16
3	2nd Relay ON	8, 16, 24
4	3rd Relay ON	16, 24, 30

2.2 Inference

Table 4 shows fuzzy rules that serve to define actions on changes that occur in inputs.

Table 4. Fuzzy Rules

Rules	Temperature	Time	Relay Condition
Rule 1	Cold	Midnight	AC OFF
Rule 2	Cold	Morning	1 AC ON
Rule 3	Cold	Noon	2 AC ON
Rule 4	Cold	Afternoon	2 AC ON
Rule 5	Cold	Night	1 AC ON
Rule 6	Cool	Midnight	1 AC ON
Rule 7	Cool	Morning	1 AC ON
Rule 8	Cool	Noon	2 AC ON
Rule 9	Cool	Afternoon	2 AC ON
Rule 10	Cool	Night	1 AC ON
Rule 11	Normal	Midnight	1 AC ON
Rule 12	Normal	Morning	1 AC ON
Rule 13	Normal	Noon	2 AC ON
Rule 14	Normal	Afternoon	2 AC ON
Rule 15	Normal	Night	1 AC ON
Rule 16	Warm	Midnight	1 AC ON
Rule 17	Warm	Morning	1 AC ON

Rules	Temperature	Time	Relay Condition
Rule 18	Warm	Noon	3 AC ON
Rule 19	Warm	Afternoon	2 AC ON
Rule 20	Warm	Night	2 AC ON
Rule 21	Hot	Midnight	1 AC ON
Rule 22	Hot	Morning	2 AC ON
Rule 23	Hot	Noon	3 AC ON
Rule 24	Hot	Afternoon	3 AC ON
Rule 25	Hot	Night	2 AC ON

3. Results and Discussion

3.1 Prototype

This test is carried out to find out the system has run according to the designed program. The author conducts prototype testing to control the output of the relay with various temperature sensor test conditions and at certain times. The design of the tool is made with several components, including the Board, ESP32, DHT22 Sensor and relay as in figure 4.

The device is connected to the IoT system displayed on ThingSpeak so that readings on the serial monitor can be displayed also on ThingSpeak. This test was carried out 7 times in the office room of the Graha Merah Putih Building. The test results are shown in Table 5.

Table 5 presents the recorded temperature and humidity values at 10-minute intervals using the DHT22 sensor. The data reveals a consistent trend where humidity drops slightly as temperature rises during midday, which aligns with expected environmental conditions. These fluctuations directly affect the fuzzy controller's activation pattern, which optimizes AC usage when critical thresholds are crossed.

Table 5 shows that the system operated according to the programmed fuzzy rules, validating the correct relay response based on input conditions. Temperature sensor readings can be displayed well on serial monitors and produce output following the rules that have been designed. From test 1 to test 7 that has been carried out, the AC On indicator successfully switches according to the designed program rules. In the office room when the time is getting night and the population of people in the room has decreased, the temperature detected is also getting lower, affecting the output of the AC indicator.

Table 5. Experiments Result

No	Time	Room temperature on serial monitor (°C)	Room temperature on Hygrometer (°C)	AC indicator (Unit On)
1	08.00	27.2	26.8	2
2	10.40	29.6	28.8	2
3	12.25	30.5	29.4	3
4	16.00	29.1	28.2	3
5	17.40	26.0	25.8	2
6	19.00	22.7	23.6	1
7	20.25	22.5	23.3	1

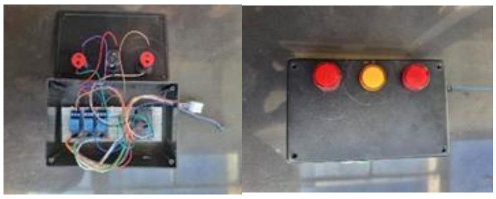

Fig. 4. Design result

3.2 Fuzzy Mamdani Method

Testing was carried out on the fuzzy logic Mamdani method. This test is carried out by comparing the results of manual and software simulation calculations. One sample is taken from testing 1 is temperature sensor 27.2 (°C) at 08.00 am.

The temperature sensor input of 27.2 (°C) lies between the warm and hot membership degrees. Then for the time of 08.00, it is located between the morning and afternoon membership degrees.

The results of the test analysis were carried out at 10.25 WIB, including the morning membership degree and the temperature read, which is 29.6°C included in the degree of heat membership so that the output is two ON indicators as shown in Figure 5. The graph shows a noticeable increase during peak hours (12:00–14:00), prompting the fuzzy logic system to activate the AC. This behavior validates the controller's responsiveness, as the system successfully adjusts output based on sensor data inputs. The graph's slope reflects the system's ability to anticipate changes, reducing temperature drift, which contributes to energy efficiency.

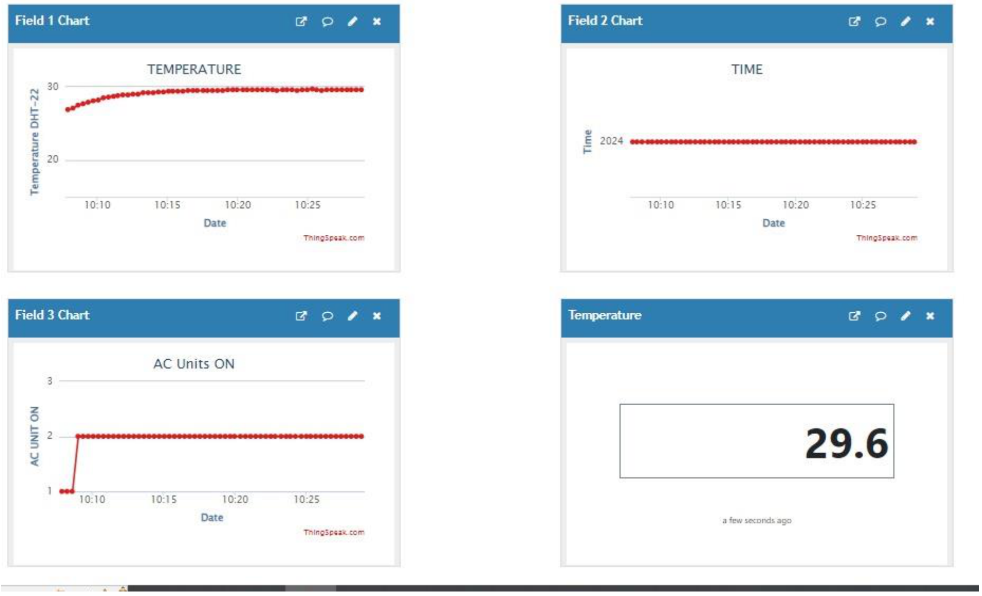

Fig. 5. ThingSpeak display

Equation (1) used to calculate the upper bound (UB) of membership value, meanwhile equation (2) used to measure the lower bound (LB). by using equation (1) and (2), the value of warm (UB), hot (LB), morning (UB), and noon (LB) can be seen on table 5. Because the input value of 27.2 is between warm and hot, the cold, cool, and normal values are 0, hence the calculation:

1. MAX value : 30
2. MIN value : 25
3. Input : 27.2

$$Upper\ Bound = \frac{(MAX\ value - input\ )}{(MAX\ value - MIN\ value)} \quad (1)$$

$$Lower\ Bound = \frac{(\text{Input} - MIN\ value)}{(MAX\ value - MIN\ value)} \quad (2)$$

$$Warm = \frac{(30 - 27{,}2)}{(30 - 25\ )} = 0{,}56$$

$$Hot = \frac{(27{,}2 - 25)}{(30 - 25)} = 0{,}44$$

$$Morning = \frac{(12 - 8)}{(12 - 4\ )} = 0{,}5$$

$$Noon = \frac{(8 - 4)}{(\ 12 - 4\ )} = 0{,}5$$

As for the calculation of time has a value of 08.00 which lies between the degrees of membership in the morning and afternoon, then the calculation:

1. MAX value : 10
2. MIN value : 5
3. Input : 8

After knowing all the implication values, then perform the rule composition with the MAX method as follows:

1. AC OFF

$$AC\ OFF = Max\ (rules\ 1) = 0 \quad (5)$$

2. 1st Relay ON

$$1^{st}\ Relay\ ON$$
$$= MAX\ (rules\ 2, 5, 6, 7, 10, 11, 12, 15, 16, 17, 21)$$
$$= (0\ ;\ 0\ ;\ 0\ ;\ 0\ ;\ 0\ ;\ 0\ ;\ 0\ ;\ 0\ ;\ 0\ ;\ 0{,}5\ ;\ 0\ ) \quad (6)$$

3. 2nd Relay ON

$$2^{nd}\ Relay\ ON$$
$$= MAX\ (rules\ 3, 4, 8, 9, 13, 14, 19, 20, 22, 25)$$
$$= 0{,}44 \quad (7)$$

4. 3rd Relay ON

$$3^{rd}\ Relay\ ON = MAX\ (rules\ 18, 23, 24)$$
$$= (\ 0{,}5\ ;\ 0{,}44\ ;\ 0\ ) = 0{,}5 \quad (8)$$

Once the max value of each output is known, then look for the boundaries of the area of the composition.

1. Calculate t1:

$$\frac{16 - x}{16 - 8}, 8 \le x \le 16$$

2. Calculate t2:

$$\frac{x - 8}{16 - 8}, 8 \le x \le 16$$
$$16 \le x \le 20$$
$$\frac{24 - x}{8}, 20 \le x \le 24$$

3. Calculate t3:

$$\frac{x - 16}{8}, 16 \le x \le 24$$

From the calculation (Eq. 1 and Eq. 2) t1, t2, t3, then the defuzzification process. The input comes from the fuzzy set of the fuzzy rule composition, while the resulting output is an exact number. In this centroid method, it is necessary to find the value of momentum and area calculation.

1. Area Calculation 1 (A1)

$$A1 = 0$$

2. Area Calculation 2 (A2)

$$A2 = \frac{(12-0)(0{,}4+0{,}5)}{2} = 5{,}4$$

3. Area Calculation 3 (A4)

$$A3 = 0{,}44 \times 9 = 3{,}96$$

4. Area Calculation 4 (A4)

$$A4 = \frac{(30-21)(0{,}44+0{,}5)}{2} = 4{,}23$$

Calculate Momentum

1. Calculate M1:

$$M1 = \int_{0}^{0} 0\,z\,dz = 0$$

2. Calculate M2:

$$M2 = \int_{0}^{12} 0{,}5\,z\,dz = [0{,}25(12)^2] - [0{,}25(0)^2] = 36$$

3. Calculate M3:

$$M3 = \int_{12}^{18} 0{,}44\,z\,dz = [0{,}22(18)^2] - [0{,}22(12)^2] = 39{,}6$$

4. Calculate M4:

$$M4 = \int_{21}^{24} \frac{z-16}{8} z\,dz$$

$$= 81[(31(24)^3 - 8(24)^2) - (31(21)^3 - 8(21)^2)] = 67{,}6$$

Based on the fuzzy region, it can be calculated the output of the crisp output of the defuzzification process:

$$Z = \frac{Momentum}{Area} = \frac{0+36+39{,}6+67{,}6}{0+5{,}4+3{,}96+4{,}23} = 10{,}53$$

From the results of manual calculations and software simulation, error results are obtained:

$$Error = \left|\frac{10{,}53-11{,}6}{11{,}6}\right| \times 100\% = 9{,}2\%$$

The error value of fuzzy calculations and measurements is 9.2% so that it can be analyzed regarding measurement accuracy on software simulation when compared to manual calculations not too much deviation difference. From the results of the implication function and the rule composition of each fuzzy rule is carried out using the MAX method. The results obtained are like Figure 6.

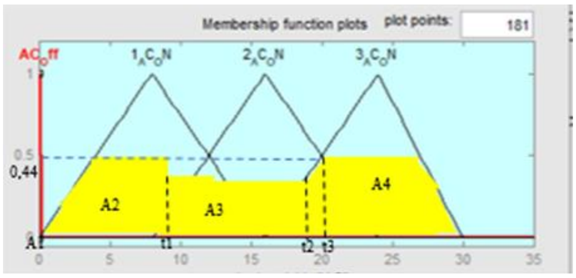

Fig. 6. The Resulting area of the composition

4. Conclusions

The AC control system using the ESP32 microcontroller with the Fuzzy Mamdani method has been successfully implemented on the prototype that has been designed. The final focus is to prove that the prototype works successfully using the Fuzzy Mamdani method with a defuzzification of 10.53 and an error percentage of 9.2% when compared to manual control, indicating acceptable precision for practical use. The results of sending data information to ThingSpeak have been successfully implemented, so the system demonstrated reliable relay switching based on environmental conditions, ensuring that the AC operated only when necessary, thereby enhancing energy efficiency. Data transmission to the ThingSpeak IoT platform functioned consistently, allowing for real-time monitoring and remote accessibility. These results affirm that the proposed fuzzy-based IoT system is effective for maintaining indoor comfort while optimizing energy usage. The combination of hardware and algorithm performance supports the feasibility of deploying this solution in real-world smart building applications.

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Additional Information