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Design of IoT-Based Control System Using Fuzzy Inference System

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Abstract

Industry 4.0 combines automation technology with cyber technology such as Internet of Things (IoT) technology. IoT services can provide a system with a huge amount of data in real-time monitoring from edge sensory nodes. However, in real-world industrial applications, IoT cannot achieve a good result in decision-making tasks unless intelligent mechanisms are integrated into it. A control system based on the combination of IoT and artificial intelligence (AIIoT) is explored in this study. This research simulated the used of IoT devices for controlling tasks and can be monitored via the internet. In addition, an artificial intelligence, i.e., a fuzzy Inference System, is proposed. First, inputs are recorded from DHT11 temperature-humidity sensor and the MPX5100DP indoor air pressure sensor. Then, the inference model converts the inputs into fuzzy sets and then calculates the output during the inference phase using predefined rules. The proposed algorithm is implemented using an ESP8266 Arduino board which can connect to the server via Wi-Fi. This prototype can record input data with errors measured by RMSE of 0.38 and 1.158 for humidity-temperature and air pressure sensors, respectively. Based on experiments, the system can respond optimally to the input changes that are manipulated through the FIS algorithm, as evidenced by using an average error of 0.0145 in five different scenarios

Keywords:
Internet of Things (IoT), decision-making tasks, AIIoT, Fuzzy Inference System (FIS), RMSE

1 Introduction

Currently, many studies integrate Internet of Things (IoT) technology into the design of closed-loop control systems. With the increasing data processing capabilities of IoT computer devices, this technology provides a tremendous amount of data from various sources. However, most of the studies involve the IoT computing unit only as a traditional "on-off" controller, which controls the actuator in two states, i.e., ‘on’ and ‘off’. Today, Artificial Intelligence (AI) is a game-changer for control systems with the intelligent capability to improve the effectiveness and efficiency. By combining IoT with AI technology (AIIoT), intelligent and connected systems can be improved and developed, e.g., industrial IoT implementations [1], smart home appliances [2], and smart cars [3]. Therefore, research related to the use of artificial intelligence combined with IoT technology needs to be explored. However, appropriate AI techniques need to be implemented. Thus, the controller can adaptively regulate non-linear and complex tasks. This research contributes to the development of control systems with the integration of AI techniques into IoT edge sensory nodes using a Fuzzy Inference System (FIS). The purpose of this research is to provide a control system that is smart, portable, and easy to develop, and present interpretability that is closer to human perception.

Several articles related to the use of FISs and IoT controllers are quoted as follows. In [4], a study explains that several sensors can be installed on Industrial IoT-based microcontrollers. Then some of these microcontrollers can be combined with each other so as to enhance the device's functionality, e.g., big data collection, real-time communication, and expandable peripherals. Moreover, in another study, a microcontroller controls the temperature and humidity inside the server room [5]. It is explained that the application of a fuzzy logic-based control system does not require a mathematical model and is optimal for nonlinear control because decisions issued only use human logic. Several phases develop a FIS, including fuzzification, inference, and defuzzification. A FIS also can be used to control temperature and humidity in oyster mushroom cultivation [6]. The FIS is applied in a miniature 80 cm3 mushroom room. The actuators used were fans and water pumps. The sensor used was SHT11 as a gauge of temperature and humidity. The results reveal that the temperature and humidity can be controlled to reach the optimum requirements for oyster mushrooms to grow. A study was also conducted to design hardware utilizing fuzzy controllers to control heat exchanger temperature [7]. In this article, an ATmega32 microcontroller is used as a fuzzy controller.

Another preliminary study provides the design and manufacture of a microcontroller-based weather monitoring system [8]. An SHT11 sensor was used to record temperature and humidity data. A barometric pressure HP03 was employed to record air pressure data. Meanwhile, an Arduino platform was created to monitor temperature and humidity [9]. The system recorded the temperature and humidity stored in the log file. This IoT-based prototype was designed in a portable size. The temperature and humidity data can be sent to the other monitoring device, e.g., smartphones or tablets, wirelessly. Another article focuses on the design of environmental condition monitoring networks [10]. It was demonstrated that fuel cells could power such a wireless network, which was possible due to the characteristic of IoT nodes, i.e., low power requirement. In another study, air pollution monitoring devices based on IoT were developed using wireless sensor networks [11]. The devices could functionally record PM2.5 pollution levels in real-time.

From the aforementioned studies, nonlinear and complex data are a hard challenge to design accurate and reliable systems. Despite monitoring systems, IoT devices can also be used as control systems. However, how to process the data in the control system domain requires different strategies that can specifically be implemented using a FIS. The combination of IoT and AI technology is a game-changer, thus doing the research related to AIIoT in control systems more practical and reasonable. This study provides a better understanding of the possibility of designing artificial intelligence-based hardware to control inputs to reach a specific target (output). This study simulates a FIS in an ESP8266 Arduino board to control the motor servo.

2 Materials and Methods

To integrate the IoT technology with the FIS, this study employed a control system with a servo motor as the actuator. An IoT-based microcontroller was utilized, i.e., ESP8266 Arduino, to process two data inputs from the air pressure sensor module and the temperature-humidity sensor module.

2.1 Algorithm

Fuzzy logic is a blur logic containing an element of uncertainty. In ordinary logic, i.e., strict logic (crips logic), two values are introduced, i.e., true or false (0 or 1). On the other hand, fuzzy logic recognizes the value between true and false (0 – 1). Truth in fuzzy logic can be expressed in degrees of truth, of which the value is from 0 to 1. A fuzzy set is a grouping of things based on linguistic variables expressed as membership functions in the universe. Membership of a value in a set is expressed in terms of membership values between 0.0 and 1.0. Fuzzy sets are based on the idea of extending the range of characteristic functions so that the function will include real numbers at intervals of 0 to 1. The membership value indicates that an item is not only true or false. A value of 0 indicates false, a value of 1 indicates true, and there are still values lying between true and false. A fuzzy logic control system is also called a fuzzy inference system (FIS). FIS is a system that can do reasoning with similar principles as humans do reasoning with their instincts. The process inside fuzzy logic controls the input given, and the resulting output must also be a certain number. The rules in linguistic language can be used as meticulous input, which must be converted first. Then the controller makes reasoning based on the rules and converts the reasoning results into conscientious output.

FIS is easily understood because it best suits human instincts. Furthermore, a Mamdani FIS is closer to human perception than the other model e.g., Takagi-Sugeno. However, the Takagi-Sugeno FIS provides outputs that are not a fuzzy set but rather a constant or linear equation. This research utilizes the Takagi-Sugeno fuzzification methods, where an IoT-based system is developed using an Arduino board, i.e., ESP8266 Arduino. The sensor used is MPX5100DP air pressure sensor and DHT11 humidity-temperature sensor. Both sensor systems convert real-world measurements into voltage. The advantages of these sensory modules are the quality of the signal, their responsiveness in terms of sensing the objects, and the data read is easily interpreted.

2.2 Design of Process

The system design consisted of designing the process, a database, and an interface graphical user interface (Fig. 1).

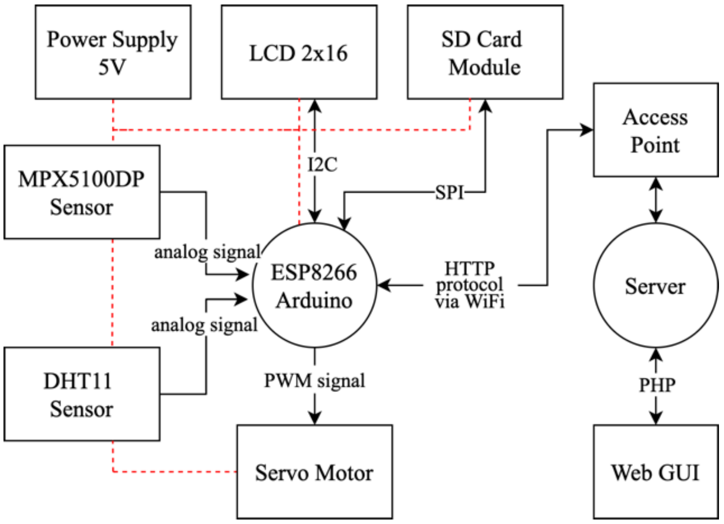


Fig. 1. The system architecture of the proposed IoT device.

2.2.1 Design of Hardware

The design of the proposed system architecture is illustrated in Fig. 1. The fig. provides an overview of the prototype and presents the data flow from the edge sensory node to the network. The input is from the temperature and humidity sensor, MPX5100DP, and DHT11 sensor via analogue signal input. All inputs were processed by the ESP8266 Arduino board. Then, the analogue data were processed and converted to digital data using an analogue-to-digital converter (ADC) inside the microcontroller. Furthermore, the data were processed using FIS, and the output will be simulated using a servo motor. The output is represented using pulse width modulation (PWM). The number is in the range of 0 to 255, which represents the rotation of the servo motor arm from 0 • to 360 •. These rotations can be used to simulate the output of FIS in real value after the defuzzification phase. Simultaneously, the output is displayed using the LCD 2x16 module and sent to the server via the HTTP Protocol. From the server, the data can be retrieved by the users using internet connections to access the website. In the end, the users can also monitor the processes of the FIS using this AIIoT prototype.

2.2.2 Design of Software

The software design was designed using a flowchart, as shown in Fig. 2. At first, initialization of internal devices on the microcontroller was done, including ADC, SPI, I2C, PWM, and Wi-Fi. Then, a fuzzy rule is initialized. These rules will be used in the next process. Next, the prototype records data on the sensors. Digital data from sensor readings are stored in the SD card via SPI. Simultaneously, these data are displayed on the LCD. Next, the FIS stages, which include fuzzification, inference, and defuzzification, are carried out. In the end, this data is sent to the server over the Wi-Fi network using the HTTP protocol. The data is also stored in a database. In addition, the server also displays these data along with the results of fuzzy calculations to simulate that this AIIoT-based device can work and may be developed in the future.

Temperature and humidity variables were made into linguistic variables through the fuzzification process. The membership function of the humidity-temperature sensor is shown in Fig. 3. To calculate the degree of membership, Eq. (1), (2), and (3) are used: Flowchart of microcontroller system is shown in Fig. 2.

Degree of Cold Membership:

$$\mu(\text{Cold}) = \begin{cases} 1; & x \le 15 \\ (20 - x)/(20 - 15); & 15 \le x \le 20 \\ 0; & x \ge 20 \end{cases} \tag{1}$$

Degree of Normal Membership:

$$\mu(\text{Normal}) = \begin{cases} 0; & x \le 15 \\ (x - 15)/(20 - 15); & 15 \le x \le 20 \\ (30 - x)/(30 - 20); & 20 \le x \le 25 \\ 0; & x \ge 25 \end{cases} \tag{2}$$

Degree of Hot Membership:

$$\mu(\text{Hot}) = \begin{cases} 0; & x \le 20 \\ (x - 20)/(30 - 20); & 20 \le x \le 25 \\ 1; & x \ge 25 \end{cases} \tag{3}$$

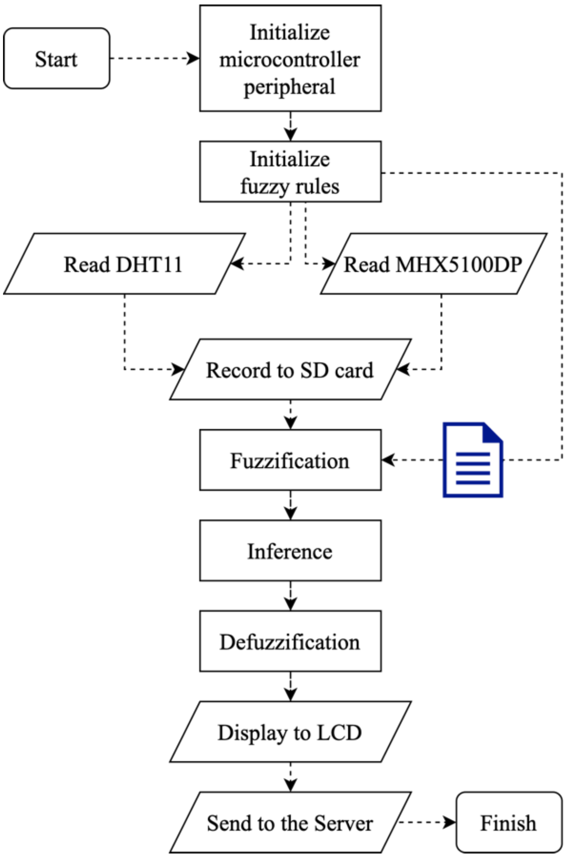
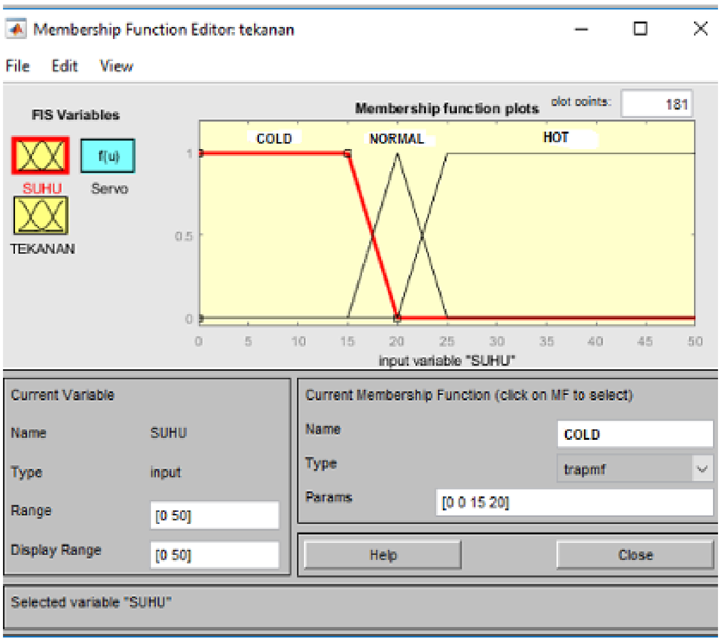


Fig. 2. Flowchart of microcontroller system

The membership function of the humidity-temperature sensor is shown in Fig. 3.



Current Variable
Name SUHU
Type input
Range [0 50]
Display Range [0 50]

Current Membership Function (click on MF to select)
Name COLD
Type trapmf
Params [0 0 15 20]

Selected variable "SUHU"

Fig. 3. DHT11 Membership function of temperature and humidity

The pressure variable was made in a linguistic/fuzzification variable, depicted in Fig. 4. The eq. to find the degree of pressure membership is shown in eq.s (4), (5), and (6):
Degree of Low Membership:

$$\mu(\mathrm{Low}) = \begin{cases} 1; & x \le 45 \\ (50-x)/(50-45); & 45 \le x \le 50 \\ 0; & x \ge 50 \end{cases} \tag{4}$$

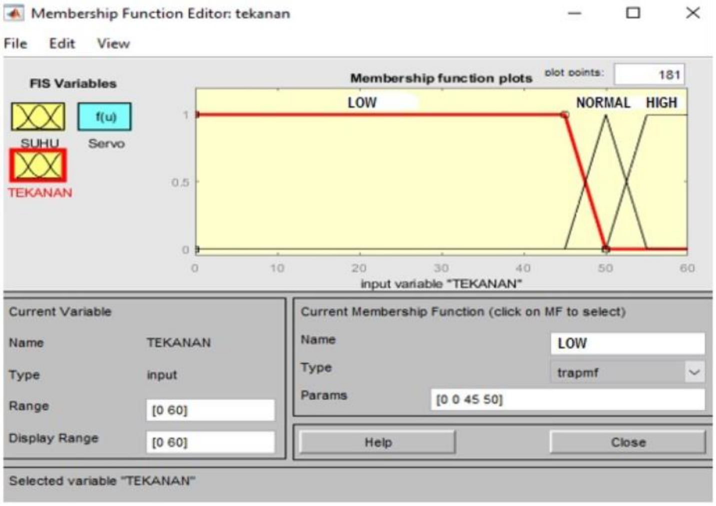
Degree of Normal Membership:

$$\mu(\mathrm{Normal}) = \begin{cases} 0; & x \le 45 \\ (x-45)/(50-55); & 45 \le x \le 50 \\ (55-x)/(55-50); & 50 \le x \le 55 \\ 0; & x \ge 55 \end{cases} \tag{5}$$

Degree of High Membership:

$$\mu(\mathrm{High}) = \begin{cases} 0; & x \le 50 \\ (x-50)/(55-50); & 50 \le x \le 55 \\ 1; & x \ge 55 \end{cases} \tag{6}$$

The pressure variable was made in a linguistic/fuzzification variable, depicted in Fig. 4.



Current Variable
Name TEKANAN
Type input
Range [0 60]
Display Range [0 60]

Current Membership Function (click on MF to select)
Name LOW
Type trapmf
Params [0 0 45 50]

Selected variable "TEKANAN"

Fig. 4. Membership function of air pressure

The following are the basic rules used to control servo motor (Table 1) and the rule values for each condition (Table 2). Design of database is shown in Fig. 5

Table 1. Rule base of servo motor

Pres-	Temperature		
sure	Cool	Normal	Hot
Low	Slightly Open	Normal Open	Rather Fully Open
Normal	Normal Open	Rather Fully Open	Almost Fully Open
High	Rather Fully Open	Almost Fully Open	Fully Open

Table 2. The remark of rule values

Servo motor condition	Values (%)
Slightly Open	20
Normal Open	40
Rather Fully Open	60
Almost Fully Open	80
Fully Open	100

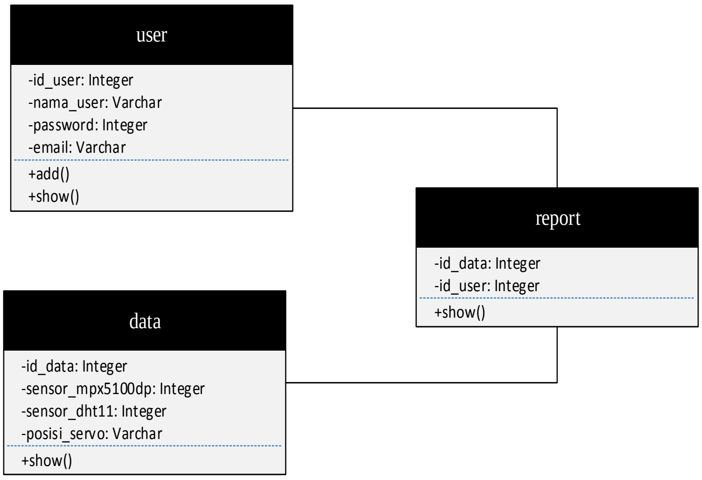


Fig. 5. Design of database

2.2.3 Design of Database

The MySQL database is used in making the webserver because the manufacturing process is quite easy compared to other software. In addition, MySQL is supported by a wide community with good compatibility with server-based programming languages. The compiled database contains tables including the Data table, User table and Report table. The User table is used as a security verification for users who access the website. The User table consists of several column names, namely: 'id_user', 'username', 'password', and 'email'. The Data table consists of 4 columns, namely: 'id_data', 'sensor_DHT11', 'sensor_MPX5100DP', and 'position_servo'. The Report table consists of 2 columns, namely: 'id_data' and 'id_user'. So this table maps the relationship between the User Table and the Data Table. The following details the data that will be used in this system, as shown in Fig. 5.

2.2.4 Design of Graphical User Interface

The interface is designed to display data from the temperature-humidity sensor (DHT11) and pressure sensor (MPX5100DP) sent from the hardware. This interface is planned as a website-based monitoring system. In this initial research, the interface is only built on a basic basis using the PHP programming language. PHP is used in this research because it is open source and supports SQL database queries. The coding is implemented on the server-side.

2.3 Evaluation

Evaluations were carried out on systems implemented, including tests on the results of coding programs, tests on the ability to read the DHT11 temperature and humidity sensor and the MPX5100DP pressure sensor embedded into the system, compared to conventional measurements. This test was performed to ensure that each component moved according to instructions. The readings from each sensor were analyzed using the Mean Absolute Error (MAE) measurement method, Root Mean Square Error (RMSE), and t-test.

MAE is the amount used to measure how close an estimate or prediction is to the final result. The t-test employed was an independent sample t-test. This test analyzed the difference between the averages of two unrelated groups. In this case, sensor readings on the system were compared with sensor readings manually. Meanwhile, RMSE is one way to evaluate linear regression models by measuring the accuracy of the estimated results of a model. The more similar the two signals, the closer the MAE and RMSE values to zero.

3 Experimental Results and Discussion.

Based on the experiments conducted, the results are as follows.

3.1 Experimental Results

Tests carried out on systems implemented included testing programs and hardware. The results from two inputs, i.e., the temperature were measured by DHT11, and MPX5100DP measured the pressure. As an output, the servo motor was used. For scenario #1, we used the temperature value of 19°C at a pressure of 52 kPa. We calculated it manually and compared it with the program coding system to determine the difference between the two calculations. The temperature is presented in Fig. 6. Variable pressure fuzzification is shown in Fig. 7

∝Normal = µNormal [19] = (19-15) / (20-15) = 4/5 = 0.8
∝Cold = µCold [19] = (20-19) / (20-15) = 1/5 = 0.2

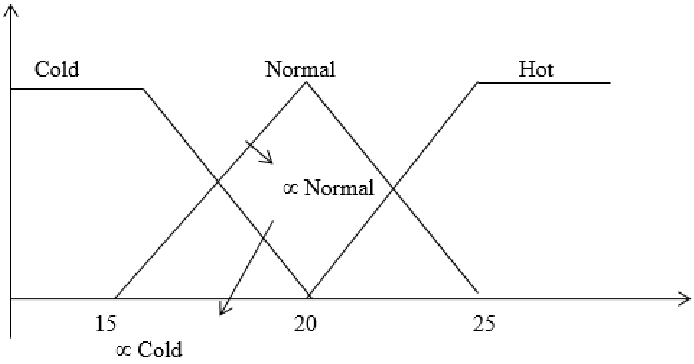


Fig. 6. Variable temperature fuzzification

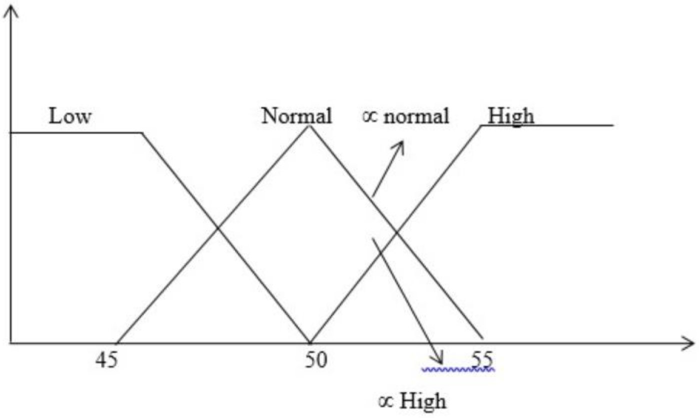


Fig. 7. Variable pressure fuzzification

Furthermore, we utilized the rule based on the Fuzzy Rule presented in Table 3.

Table 3. Rule base or fuzzy rule

Pressure	Temperature		
	Cold **(0.2)**	Normal **(0.8)**	Hot
Low	Slightly open	Normal open	Multiple open
Normal **(0.6)**	Normal open **(0.2)**	Multiple open **(0.6)**	Wide open
High **(0.4)**	Multiple open **(0.2)**	Wide open **(0.4)**	Fully open

∝Normal = µNormal [52] = (55-52) / (55-50) = 3/5 = 0.6
∝High = µHigh [52] = (52-50) / (55-50) = 2/3 = 0.4

Furthermore, we utilized the rule based on the Fuzzy Rule presented in Table 3. The process number of the Rule Value description resulted in the rotation value of the servo motor [0% – 100%] = $[0^{o} - 360^{o}]$. Then, in the form of an 'if ... then ...' statement, the following results were obtained.

1. If *the temperature is cold* and *the pressure is normal*, then the servo response is normally open.
2. (∝ cold temperature ∩ ∝ normal pressure = 0.2)
3. If *the temperature is normal* and *the pressure is normal*, then the servo response is multiple open
4. (∝ normal temperature ∩ ∝ normal pressure = 0.6)
5. If *the temperature is cold* and *the pressure is high*, then the servo response is multiple open
6. (∝ cold temperature ∩ ∝ high pressure = 0.2)
7. If *the temperature is normal* and *the pressure is high*, then the open servo response is widely open
8. (∝ normal temperature ∩ ∝ normal pressure = 0.4)

From the results, the weighted Z average value was obtained through the following eq..

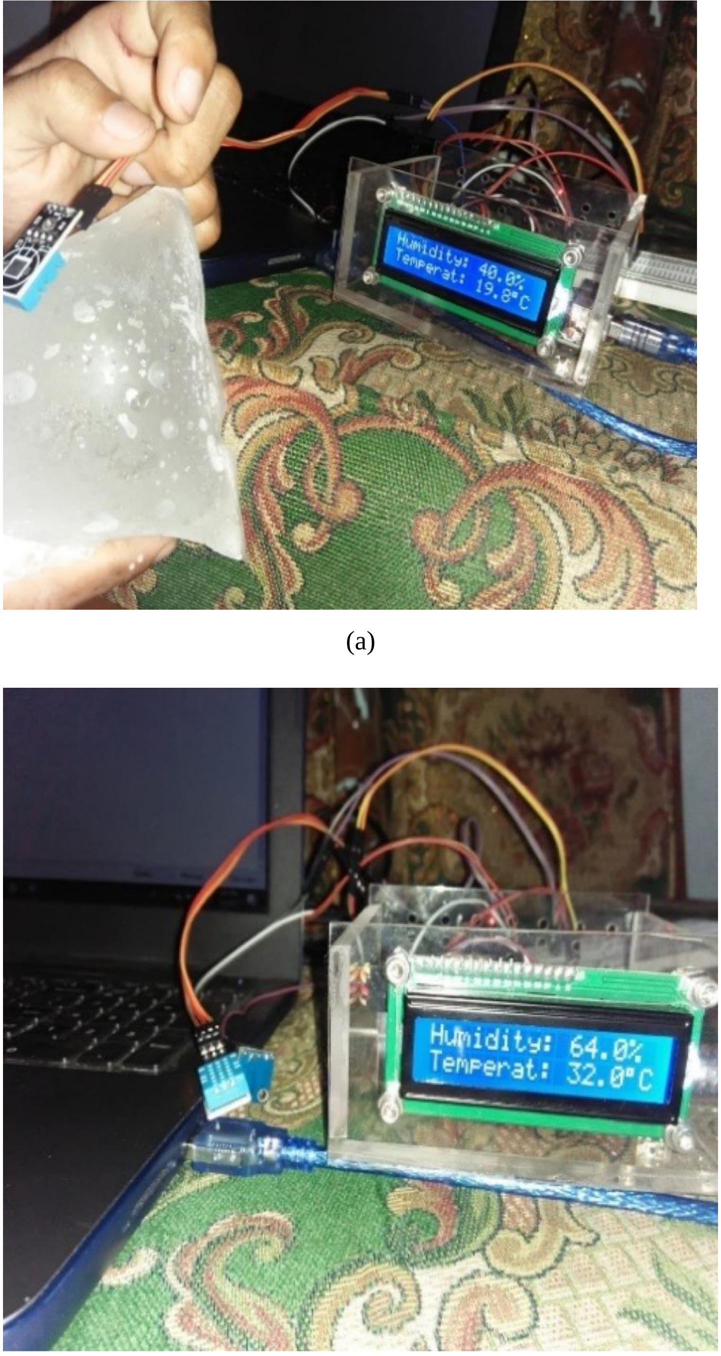
$$Z = \frac{0.6\,(60) + 0.4\,(80) + 0.2\,(40) + \ 0.2\,(60)}{0.6 + 0.4 + \ 0.2 + \ 0.2}$$

$$= \frac{36 + 32 + 8 + 12}{1.4} = 62.5$$

Table 4. Test results of DC servo motor response

Scenario	Input		Output servo motor		Diff (e)
	Temp (^{o}C)	Pressure (kPa)	FIS Calculation (%)	FIS prototype (%)	
1	19	52	62.50	64.00	0.0150
2	17	52	57.78	59.20	0.0142
3	19	51	60.00	61.40	0.0140
4	17	51	54.29	55.60	0.0131
5	19	101	68.00	69.60	0.0160
Average of error					0.0145

Test results of DHT11 sensor in (a) cold and (b) normal condition is shown in Fig. 8



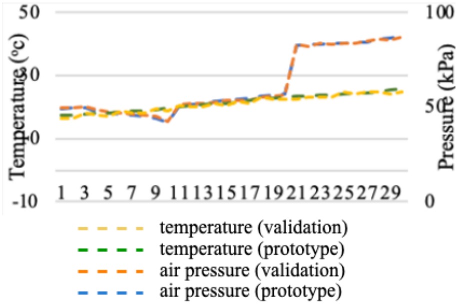
(a)

(b)

Fig. 8 Test results of DHT11 sensor in (a) cold and (b) normal condition.

Meanwhile, calculations using the computation coding system program produced a value of 64. In short, the calculation results between manual and computation coding system programs obtained a difference (error) of 0.0150. Furthermore, the results of testing the system with several inputs in a similar way in five scenarios are shown in Table 4. From the five experiments with the input values of temperature and pressure readings, the average error between the calculation results and the results of coding servo motor response programs from the system was 0.0145.

Comparison of measurement by using the sensor module and validation device is shown in Fig. 9.



[Temperature MAE]	[0.360]
[Temperature RMSE]	[0.380]
[Air pressure MAE]	[1.023]
[Air pressure RMSE]	[1.158]

Fig. 9. Comparison of measurement by using the sensor module and validation device

Testing the temperature and humidity sensor (DHT11) was carried out in cold, normal, and hot temperatures by providing a certain treatment to the sensor. If the DHT11 sensor had no errors, the Serial Monitor display would have contained data sent by the Arduino board. The sensor was then treated to measure the cold ambient temperature, and the temperature and humidity readings were obtained, as shown in Fig. 8 (a). Meanwhile, if the sensor was treated in normal conditions, the temperature and humidity readings were obtained, as shown in Fig. 8 (b). For evaluation, the prototype is compared to the validation tools. The humidity was measured conventionally using a Thermo-hygrometer gauge, and the pressure was measured using a Magnehelic gauge. Fig. 9 is the measurement graph for each sensor.

Independent sample t-test tests were carried out on each variable, namely the temperature and humidity DHT11 sensor readings from the system, temperature and humidity readings by the Thermo-hygrometer gauge, MPX5100DP pressure sensor readings from the system, and pressure readings using the Magnehelic gauge were performed with the help of SPSS software with an H0 hypothesis. H0: there is no significant difference between the sensor readings of the system and the manual measuring device used.

3.2 Discussion

The test results of the coding program algorithm for simulation scenario 1 (19^{o}C temperature and 52 kPa pressure), using calculation with crisp value at 19oC temperature on DHT11 sensor and 52 Pa pressure on MPX5100DP sensor, resulted in a DC servo motor response of 64%. Meanwhile, based on the results of manual calculations for this scenario, from two inputs, namely the DHT11 sensor and MPX5100DP sensor, the output of the DC servo motor response was 62.5%. Hence, the difference between the results of manual calculations and direct measurement through the system algorithm was 1.5% (0.015). Simulation 2 (17oC temperature and 52 kPa pressure) produced a DC motor response of 59.2%. Simulation 3 (19oC temperature and 51 kPa pressure) resulted in a DC motor response of 61.4%. Simulation 4 (17oC temperature and 51 kPa pressure) produced a DC motor response of 55.6%, and simulation 5 (19oC temperature and 101 kPa pressure) produced a DC motor response of 69.6%. Thus, the average difference with the calculation results, according to Table 4, was 0.0145. It is a relatively small number and can be accepted for a measurement involving a complex system, namely the sensor, transmitter, microcontroller, and the action of the actuator. This difference can occur in the sensor sensing the measurement variable because, as is known, all electronic equipment does not produce an exact value. There must be a change every time the change is still within the tolerance limits given. From this, the algorithm used for coding has been able to produce the expected response output.

Furthermore, the readings of the DHT11 sensor installed on the system are compared with the readings of the Thermo-hygrometer for testing 30 times. The results obtained based on the statistical calculation of the independent sample t-test were at an error rate of 5%. There is no significant difference between the two readings of these two devices. In addition, we validated the MPX5100DP sensor readings compared to values recorded using the Magnehelic device during 30 tests. The results obtained based on the statistical calculation of the independent sample t-test is an error rate of 5%. It turned out that there was no significant difference between the two readings of the two validation tools. In other words, the IoT prototype can work according to the predefined specifications, as evidenced by the values that can be displayed via the LCD and on the webserver. Some notes related to the reliability of the designed components, collaborative data retrieval, and the security potentials can be researched and developed further. As a suggestion for further study, the alternative techniques of AI, e.g., Artificial Neural Networks (ANN) and Genetic Algorithms (GA), can be explored to increase system accuracy and reliability.

4 Conclusions.

In a nutshell, the IoT prototype based on the Fuzzy Inference System could be implemented in decision-making tasks, i.e., simulated to control the response of the servo motor. The experiments revealed that the measurement variables were not statistically different from the reference system, with an RMSE of 0.38 for temperature measurements and 1.158 for air pressure measurements. In addition, the outputs can be displayed to the webserver with an average error of 0.0145 in five different scenarios compared to the manual calculations. The designed system is feasible to be developed for the next generation IoT system, i.e., AIIoT integrations.

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