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IoT-Based Real-Time Control System for Variable Air Volume (VAV) Air Conditioning Using Arduino, Temperature and Humidity Sensor, Actuators, Damper, and Node-RED

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ABSTRACT

This research is intended to develop an IoT-based real-time control system for variable air volume air conditioning. This had been built using Node-RED, which provides optimized settings based on collected data from Arduino UNO microcontrollers and DHT11 sensors. The control system targeted supply air temperature and humidity as primary controlled variables that follow the Malaysian Standard MS 1525:2014. It uses Belimo NM24A and LM230A-S actuators for damper position control, providing the system with two-position and modulating control modes. Experimental results show that good air temperature and humidity control have been achieved, with very small power and energy consumption differences between the two modes. It further provides an interface to monitor and actuate the VAV system via the Node-RED dashboard.

1. Introduction

Integrating digital skills in vocational education is essential to align with industry standards, particularly in the Industrial Revolution 4.0 (IR 4.0) era. These skills, as emphasized in the Malaysian Board of Technologists (MBOT) Programme Learning Outcome (PLO), focus on the application of Internet of Things (IoT) principles [1]. One of the key sectors benefiting from IoT implementation is the heating, ventilation, and air conditioning (HVAC) industry, which plays a critical role in maintaining indoor environmental quality and energy efficiency [2-4]. According to the Malaysian Standard MS1525:2014, room comfort is influenced by air temperature, relative humidity, and air

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movement [5-6]. These factors must be carefully managed to ensure human comfort and energy conservation within HVAC systems [7-9].

Despite advances in HVAC technology, challenges persist in maintaining optimal indoor conditions while minimizing energy consumption [8]. Some studies reveal that traditional HVAC systems often fail to comply with local comfort guidelines, relying on fixed set points that may not adapt effectively to varying environmental loads [5][10]. For example, the preferred indoor temperature for comfort is typically higher than the standard settings, highlighting inefficiencies in energy use [2][9][11]. Additionally, Variable Air Volume (VAV) systems, which rely on Direct Digital Control (DDC) to regulate temperature and airflow, face limitations in dynamic real-time control and energy optimization [9]. These systems require enhanced control strategies to adapt to fluctuating conditions and ensure compliance with regulatory standards [12].

The industry commonly uses BACnet and Modbus as controllers in HVAC systems [13-14]. However, these systems often limit the flexibility and ease of integration required for emerging IoT-based applications for education purposes [15]. Given the limitations of existing HVAC systems, there is a pressing need to develop a real-time, IoT-based control framework to optimize VAV air conditioning systems [4][10][16]. To address these challenges, this research proposes an IoT-based real-time control system for a Variable Air Volume HVAC system, leveraging Arduino, Node-RED, and low-cost sensors to optimize supply air temperature and humidity while adhering to Malaysian standards.

The objectives are to develop VAV system control of temperature and humidity, to test VAV system control, and to ensure compliance with MS1525:2014 standards using Arduino UNO microcontroller, DHT11 sensors, and Belimo damper actuators with the Node-RED. By incorporating modulating and two-position control strategies, this research seeks to enhance the operational efficiency and adaptability of HVAC systems while providing a practical solution for industry adoption[17-21].

2. Methodology

2.1 Materials

The materials used in this research included components for developing and testing the IoT-based Variable Air Volume (VAV) system. The controller selected for use was an Arduino UNO microcontroller, which is responsible for processing sensor inputs and generating actuator signals[1][4][22]. The DHT11 sensor was used for temperature and relative humidity measurements, giving critical feedback to the control algorithm [18][23-24]. The actuators employed were Belimo NM24A and LM230A-S for damper control [14]. They were selected because of the compatibility of the actuators with direct digital control systems and their performance efficiency [4]. Further, a 4-inch Prudential VAV box was used to simulate realistic HVAC conditions and represent actual experimental conditions [25-26]. The software used in this research was Node-RED, a flow-based programming tool, which facilitated the development of the IoT-based control system. Node-RED provided a user-friendly interface to integrate the Arduino microcontroller, sensors, and actuators, as well as to implement the control logic and visualization dashboard [27-29].

The overall system architecture, as depicted in Figure 1, consists of the process of the Arduino Uno microcontroller, which is responsible for collecting sensor data, processing control logic, and actuating the damper. DHT11 sensor works to measure the temperature and relative humidity of the supply air. Belimo NM24A and LM230A-S actuators provide damper position control in modulating and two-position modes, respectively. Node-RED platform serves as the IoT interface, integrating the Arduino Uno, sensors, and actuators. It also provides a user-friendly dashboard for monitoring and controlling the system. The Arduino Uno microcontroller is the core of the control system, interfacing with the sensors and actuators. It collects temperature and humidity data from the DHT11 sensor, processes the information, and generates the appropriate control signals for the Belimo actuators to adjust the damper position. The Node-RED platform serves as the IoT interface, connecting the Arduino Uno to the user dashboard.

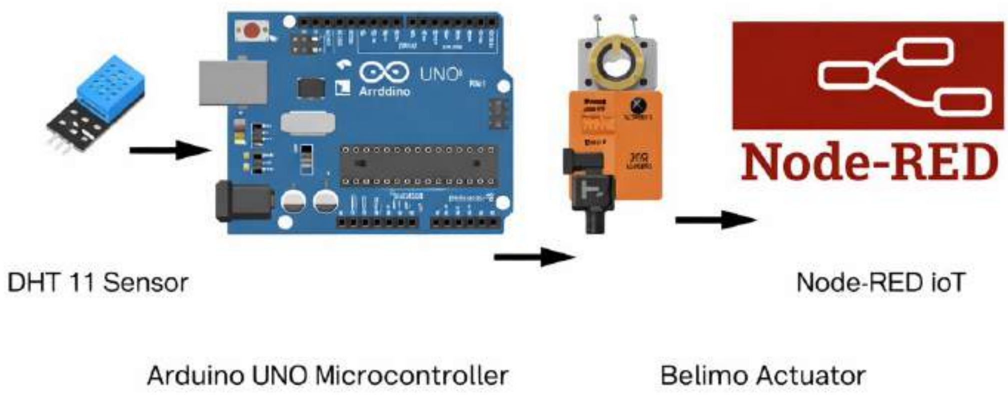


Fig. 1. Infographic of integration between Arduino UNO and Node-RED flow for the VAV control system

2.1.1 Arduino Uno Algorithm

Figure 2 shows the infographic for the work process using the Arduino Uno algorithm. The Arduino Uno microcontroller was programmed to collect temperature and humidity data from the DHT11 sensor, process the information, and send control signals to the Belimo actuators. Figure 3 shows the prompt for uploading the work application to Arduino Uno Hardware. Figure 4 shows uploading the work application for Arduino UNO.

1. Read temperature and humidity data from the DHT11 sensor at regular intervals
2. Process the sensor data and calculate the error between the measured values and the desired setpoints
3. Determine the appropriate control action based on the error, using two-position or modulating control algorithms
4. Generate control signals to actuate the damper position via the Belimo actuators
5. Transmit the sensor data and control actions to the Node-RED platform for monitoring and data visualization.
6. Implement a safety mechanism, such as damper position limits to prevent system failure.

Fig. 2. Infographic for Arduino Uno algorithm

```
#include <DHT.h>

#define DHTPIN 2   // Pin where the DHT11 is connected
#define RELAY 4    // PC relay pin
#define ANALOG A0     // Analog connnected to the mosfet
#define VCCRELAY 10  // Relay pin for voltage management

DHT dht(DHTPIN, DHT11);

float airHumTemperature = 0.0;    // Set point temperature in Celsius
float airHumHumidity = 0.0;       // Set point humidity in percentage

void setup() {

 Serial.begin(9600);
 pinMode(RELAY,   OUTPUT);
 pinMode(VCCRELAY,10,   OUTPUT);

void loop() {

 // Analog voltage output based on your humidity
float airHumTemperature = dht.readTemperature;
float airHumHumidity = dht.readHumidity();

 // Relay Management
int analogValue  = = analogRead(ANALOG);   // 3\ humidity
int percentage = analogValue / 2;
```

Fig. 3. Prompt for Uploading Work Application to Arduino Uno Hardware

```
IoT_Based_VAV_Box_Using_Node_RED
delay(2000);

float humidity = dht.readHumidity();
float temperature = dht.readTemperature();

// Analog voltage reading (based on hardware your hardware)
int voltageRaw = analogRead(VOLTAGE_PIN);
float voltage = * voltageRaw * (5.0 / 1023.0/sale the raw readi

Serial.print(Humidity: ");
Serial.print(Voltage: );
Serial.print(("Temperature: ");
Serial.print(Voltage:);
Serial.print(Voltage: );
Serial.print(Voltage: );
Serial.print();

// Control relay based on set points
if (temperature > setPointTemperature || humidity > setPointHumidity) {
  digitalWrite(RELAY_PIN, HIGH); // Turn on relay
} else {
  digitalWrite(RELAY_PIN, LOW);  // Turn off relay
}

// Your code to send temperature, humidity, voltage, and relay status to Node-RED via serial or other means
```

```
Send
16:15:02.007 -> Humidity: 86.00 %  Temperature: 28.90 °C
16:15:04.049 -> Humidity: 86.00 %  Temperature: 28.90 °C
16:15:06.045 -> Humidity: 86.00 %  Temperature: 28.90 °C
16:15:08.049 -> Humidity: 86.00 %  Temperature: 29.90 °C
16:15:10.099 -> Humidity: 86.00 %  Temperature: 29.00 °C
16:15:12.115 -> Humidity: 86.00 %  Temperature: 29.10 °C
16:15:14.322 -> Humidity: 86.00 %  Temperature: 29.10 °C
16:15:16.133 -> Humidity: 86.00 %  Temperature: 29.10 °C
16:15:18.255 -> Humidity: 86.00 %  Temperature: 29.10 °C
16:15:20.425 -> Humidity: 86.00 %  Temperature: 29.20 °C
16:15:23.450 -> Humidity: 86.00 %  Temperature: 29.20 °C
16:15:24.491 -> Humidity: 86.00 %  Temperature: 29.10 °C
16:15:28.413 -> Humidity: 86.00 %  Temperature: 29.10 °C
16:15:28.492 -> Humidity: 86.00 %  Temperature: 29.20 °C
16:15:30.491 -> Humidity: 86.00 %  Temperature: 29.20 °C
16:15:36.492 -> Humidity: 86.00 %  Temperature: 29.20 °C
Autoscroll  Show timestamp  Newline  9600 baud
```

Fig. 4. Uploading Arduino Uno code

2.1.2 Node-RED

Node-RED, a visual programming tool, was used to develop the IoT-based control system for the VAV air conditioning. The Node-RED flow is shown in Figure 5. These procedure outlines were executed on the Arduino Uno to control the VAV system. It includes reading sensor data, calculating errors from set points, adjusting the damper position using a PID controller, and communicating the system status to Node-RED. The algorithm is designed to maintain the temperature and humidity within acceptable limits while optimizing energy usage. Figure 6 shows the node-RED flow process.

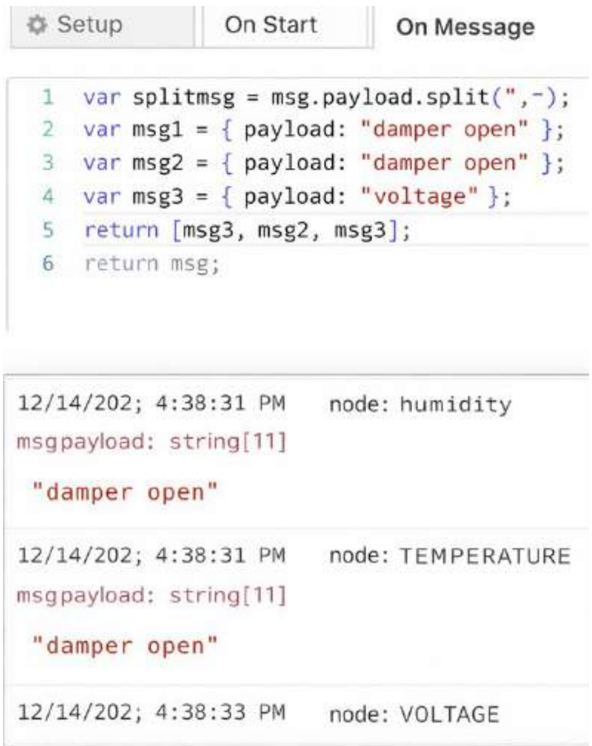


Fig. 5. Node-RED flow process [4][16]

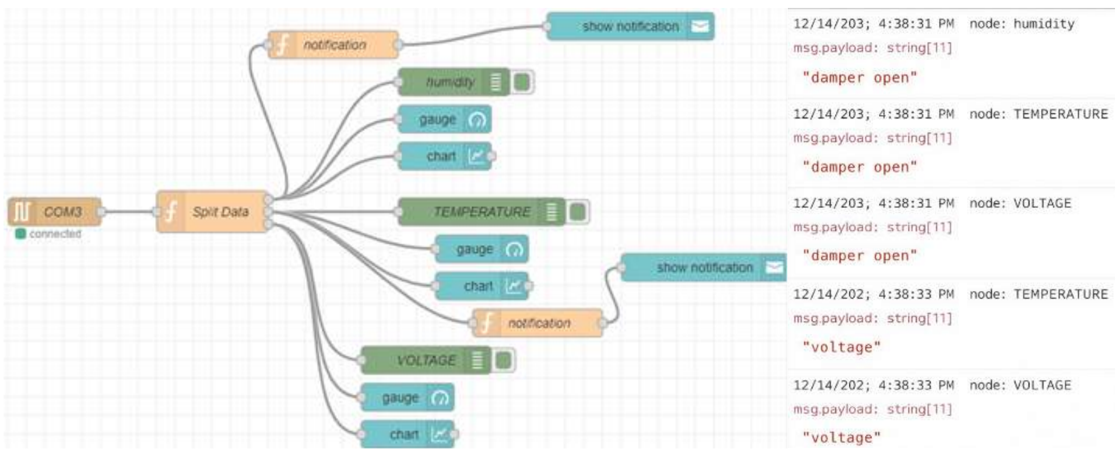


Fig. 6. Node-RED Flow for VAV Control System

2.1.3 Integration and Communication:

Figure 8 diagram shows the integration of Arduino UNO and Node-RED flow for the VAV control system. Key components include receiving sensor data from Arduino, implementing control algorithms, providing a user interface, storing data, and triggering alerts. Figure 7 was the Infographic of integration between Arduino UNO and Node-RED flow for the VAV control system.

The Arduino Uno and Node-RED communicate via serial communication at a baud rate of 9600. The Arduino sends sensor readings as a comma-separated string, which is parsed by a Function node in Node-RED. Control signals from Node-RED are sent back to the Arduino as a single numeric value representing the desired actuator position."

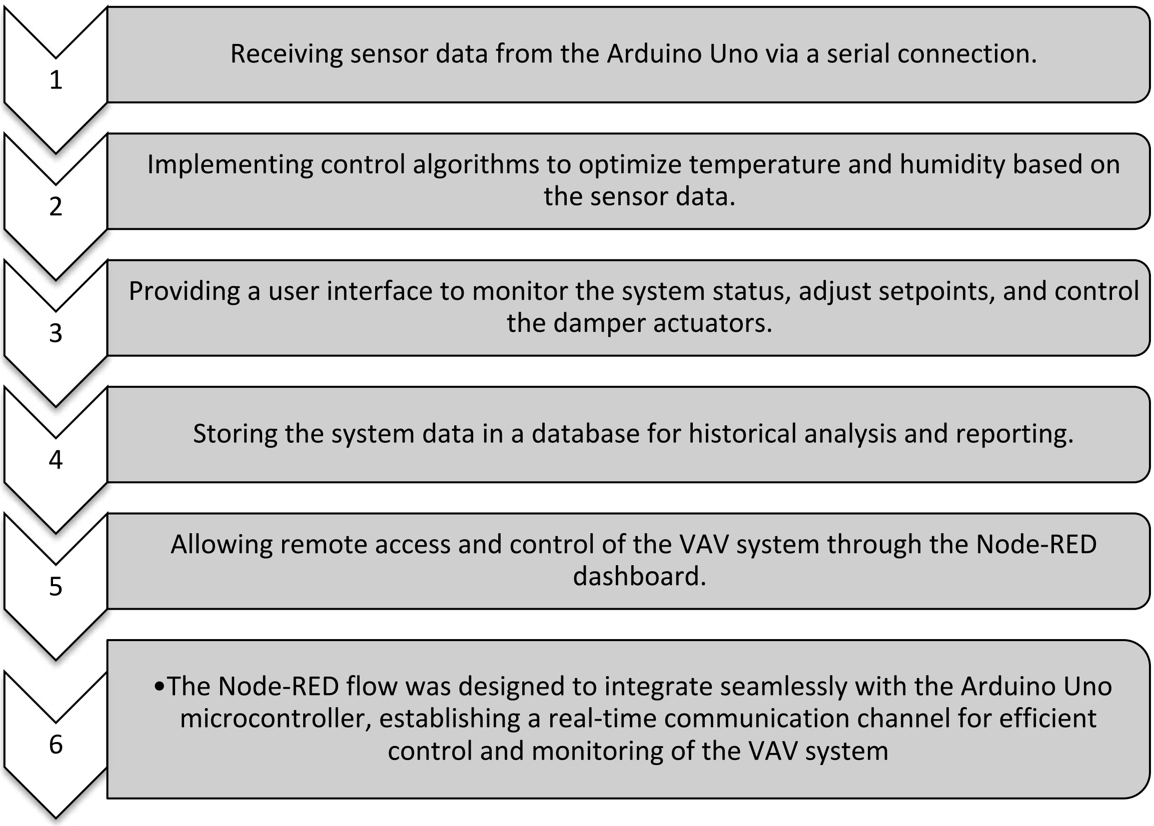


Fig. 7. The integration of Arduino UNO and Node-RED flow for the VAV control system

2.2 Experimental Scope and Parameters

The experimental setup aimed to assess the IoT-based VAV system's performance in various environmental settings. Two-position control with fixed set points (25°C and 60% RH) and modulating control with movable ranges (23–26°C and 55–70% RH) were the two control techniques that were used for 2 types of actuators. Specifically, the Belimo NM24A actuators were used for two-position control with fixed setpoints, while the Belimo LM230A-S actuators were employed for modulating control with adjustable setpoints. Monitoring variations in temperature and humidity, damper locations, and energy usage were all part of the study's scope. Actuator efficiency and total system performance were examined by recording parameters like voltage, current, and power consumption. Table 1 shows the experimental parameters.

The experiments were carried out in a small-scale test room that was representative of a typical indoor space. The dimensions of the room were 20 ft x 32 ft x 11 ft. A schematic of the experimental setup is shown in Figure 8. To capture the environmental conditions within the test room, temperature, and humidity sensors were strategically placed at multiple locations, ensuring comprehensive space monitoring. The damper position was recorded using feedback from the Belimo actuators, and power consumption was measured at the system level.

Table 1
Experimental Parameters

Parameter	Value
Room Dimensions	20 ft x 32 ft x 11 ft
Sensor Locations	1
Experimental Duration	3 hours
Data Collection Interval	1 second

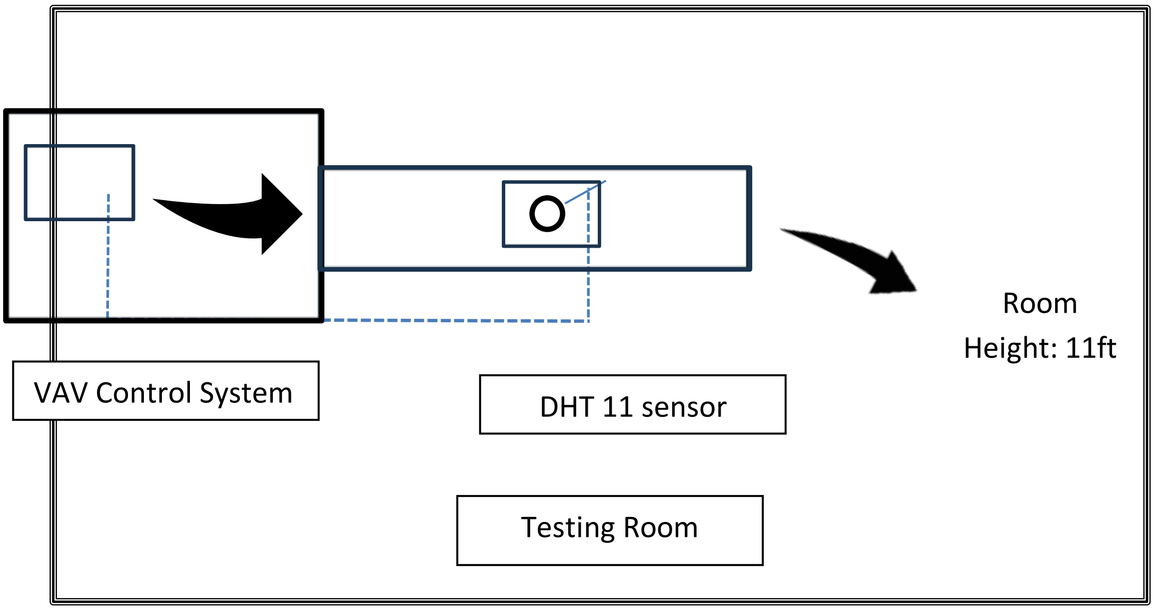


Fig. 8. Room illustration with VAV Box and sensor location

2.3 Devices, Machines, and Settings

The experimental setup incorporated a Node-RED-based IoT framework for real-time data processing and visualization. The Arduino UNO was programmed to communicate with the DHT11 sensor and the Belimo actuators, controlling damper positions based on the measured environmental variables. The VAV box was configured to simulate temperature and humidity conditions. Detailed specifications for the Arduino Uno are provided in Table 2.

Table 2
Arduino Uno Specifications

Component	Specification
Microcontroller	ATmega328P
Operating Voltage	5V
Digital I/O Pins	14
Analog Input Pins	6
Flash Memory	32 KB
SRAM	2 KB
EEPROM	1 KB

The temperature and humidity sensor used in the experimental setup was the DHT11, which has an accuracy of ±2°C for temperature and ±5% RH for relative humidity in Table 3.

Table 3
DHT11 Sensor Specifications

Parameter	Value
Operating Voltage	3.5-5.5V DC
Temperature Range	0°C to 50°C
Humidity Range	20-90% RH
Temperature Accuracy	±2°C
Humidity Accuracy	±5% RH
Response Time	6s
Interface	Digital

The Belimo actuators are stated in Table 4. The VAV box employed in the experiment was a Prudential 4-inch unit, as detailed in Table 5. A digital clamp meter (UT200+ series) measured voltage, current, and power during operation with voltage range from 0 to 600V, current range from 0 to 400A, and power range from 0 to 240kW.

Table 4
Belimo Actuator Specifications

Electrical data	NM24A	LM230A-S
Nominal voltage	AC 24V, DC 24V 50/60 Hz	AC 100…240V 50/60 Hz
Nominal voltage range	AC/DC 19.2…28.8V	AC/DC 85…265V
Power consumption in operation	1.5W	1.5W
Power consumption in rest position	0.2W	0.5W
Torque Rating	10Nm	5Nm
Control	Open/close, 3 points	Open/close, 3 points

Belimo NM24A and LM230A-S actuators were used to control the damper positions. The actuators were chosen due to their compatibility with DDC systems and their performance efficiency. A 4-inch Prudential VAV box was used to simulate realistic HVAC conditions and represent actual experimental conditions. The experiment was conducted in a controlled office environment over three hours [30].

Table 5
VAV Box Specification

Parameter	Value
Size	4 inches
Air Volume Range	44-200 M / 75-340 CMH

2.4 Analysis Methods

The analysis assessed the system's ability to maintain the target temperature and humidity ranges according to the Malaysian standard MS 1525:2014, [31] as shown in Table 6. To confirm the ability of the equipment to meet the humidity and temperature requirements, the collected data was analysed using the following methods which are (1) comparing the temperature and humidity values to the acceptable ranges specified in MS 1525:2014, (2) analysing the damper position to verify it properly responds to the control commands, (3) monitoring and comparing the power consumption under both control modes to evaluate energy efficiency and (4) evaluating the overall system performance by considering factors like response time, stability, and accuracy [32].

Table 6
Control Variables and set points range refer to the Department of Malaysian Standard MS1525:2014.

Optimal Control	Control Variable Supply Air Temp. (^{0}C)	Relative humidity (RH %)
Set points with range	23-26	55-70%
Set points a value	25	60

2.5 Schematic Design

The schematic design for the experimental setup consisted of interconnections between the Arduino UNO, DHT11 sensor, Belimo actuators, and Node-RED platform. The Node-RED interface facilitated real-time monitoring and control, enabling adjustments to set points and visualization of system behaviour [22]. Figure 9 illustrates the schematic diagram for the conceptual framework and shows the physical connections between the Arduino Uno, DHT11 sensor, Belimo actuators, and Node-RED. The Arduino acts as the central microcontroller, receiving sensor data and actuating the dampers based on the control algorithms implemented in Node-RED.

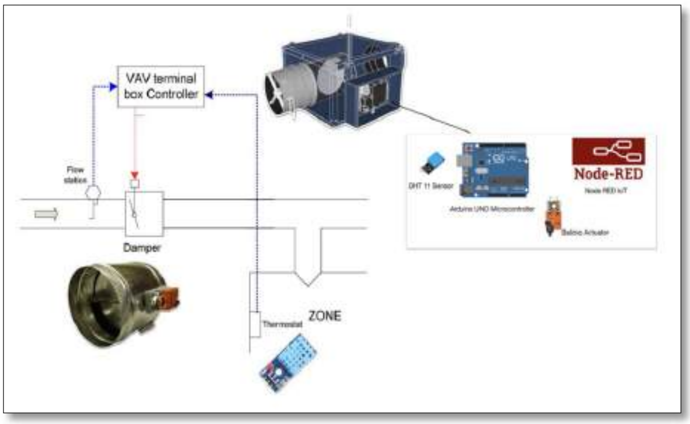
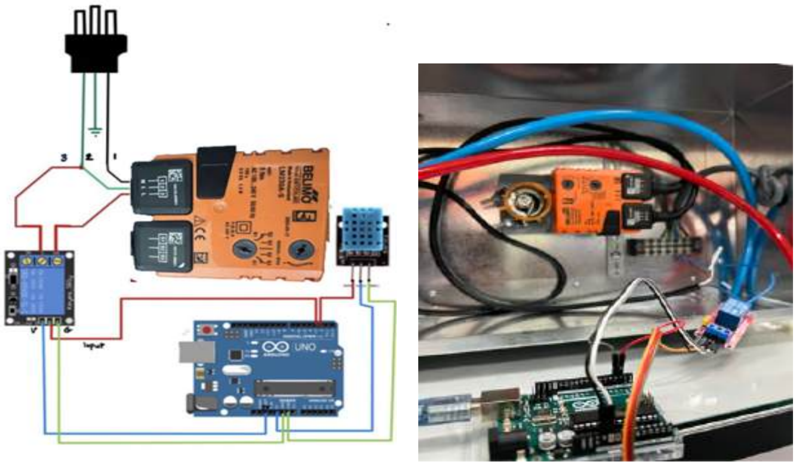


Fig. 9. The schematic diagram for the conceptual framework of the IoT-based VAV control system

The wiring diagram assembly of the Prudential VAV box was used to provide a clear understanding of the system architecture. The wiring Diagram for VAV Control System is shown in Figure 10. The actual wiring for the VAV control system is shown in Figure 11.



(a) (b)

Fig. 10. (a) Wiring Diagram for VAV Control System and (b) Actual wiring for VAV Control System

The Node-RED dashboard provided a web-based interface for real-time monitoring and control of the VAV system, as shown in Figure 11. The dashboard displayed the temperature, humidity, and damper position, allowing users to adjust set points and monitor system performance. The Arduino UNO microcontroller acted as the central processing unit, interfacing with the DHT11 sensor and Belimo actuators. Node-RED, a graphical programming tool, was used to develop the control logic and provide a user-friendly dashboard for monitoring and controlling the system.

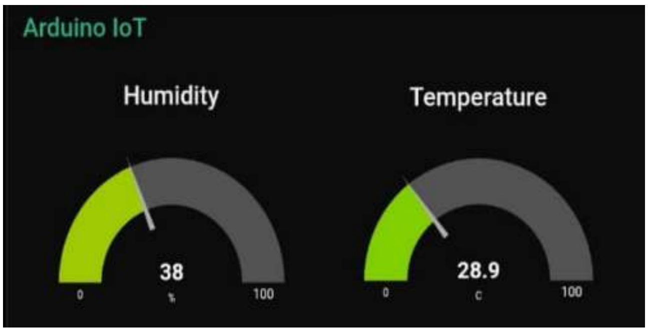


Fig. 11. Node-RED dashboard interface for monitoring and controlling the VAV system

2.6 Mathematical Equations

The control algorithms implemented in the Node-RED framework were based on proportional-integral-derivative control principles. The input variables were the measured temperature and humidity values, while the output variables were the damper position commands sent to the Belimo actuators.

The control law for the temperature loop can be expressed as:

$$UT = Kp * (Tsp - Tm) + Ki * \int(Tsp - Tm)\, dt + Kd * d(Tsp - Tm)/dt$$

where UT is the control output (damper position), Kp is the proportional gain, Ki is the integral gain, Kd is the derivative gain, and e is the temperature error.

Similarly, the control law for the humidity loop can be written as:

$$UH = Kp * + Ki * \int dt + Kd * d/dt$$

where UH is the control output, Kp is the proportional gain, Ki is the integral gain, Kd is the derivative gain, and e is the humidity error [33-34].

Mathematical equations were used to calculate power consumption expressed as:
(P=VIP = VIP=VI) and energy efficiency [35].

Assumptions included constant environmental conditions during each experiment and accurate sensor readings. The actuators were assumed to respond instantaneously to control signals. These assumptions ensured the results and simplified the analysis of the system's performance [36-37].

2.7 Limitations

The study had several limitations, including a single VAV box, which may not fully represent the complexities of larger HVAC systems. The experimental duration of three hours provided limited insight into long-term performance and energy consumption. A controlled environment may not account for external factors such as ambient temperature and humidity. Further research with more extensive testing and diverse setups was recommended to validate the findings and enhance system scalability.

3. Results and Discussion
3.1 System Performance
3.1.1 Effects of changes in temperature and humidity with range-set points (23–26 °C, 55– 70%) towards actuators

Table 7 shows values for temperature and humidity set points with range, voltage, and ampere for damper action using actuator NM24A. The set points give the actuator an order to open or close the damper. The value of the voltage and ampere of the actuator was measured using a clamp on a meter.

Table 7
The set points with damper actuator NM24A, 24V

Temperature, ^{0}C	Humidity, % RH	Ampere, A	Voltage, V	Power, W	Damper actuator NM24A
30	60	0.06	24.67	1.5	Damper open
29	60	0.06	24.67	1.5	Damper open
28	60	0.06	24.65	1.5	Damper open
27	60	0.06	24.64	1.5	Damper open
26	60	0.06	24.64	1.5	Damper open
25	60	0.06	24.65	1.5	Damper open
24	60	0.06	24.64	1.5	Damper open
23	61	0.06	3.33	0.2	Damper Close
22	62	0.06	3.33	0.2	Damper Close
21	62	0.06	3.33	0.2	Damper Close
22	62	0.06	3.33	0.2	Damper Close
23	61	0.06	24.64	1.5	Damper open
24	61	0.06	24.64	1.5	Damper open
25	61	0.06	24.64	1.5	Damper open
26	61	0.06	24.64	1.5	Damper open
27	62	0.06	3.33	0.2	Damper Close

Table 8 shows values for temperature and humidity set points with range, voltage, and ampere for damper action using actuator LM230A-S. The set points give the actuator an order to open or close the damper. The value of the voltage and ampere of the actuator was measured using a clamp on a meter.

Table 8
The set points with damper actuator LM230A-S, 240V

Temperature, ^{0}C	Humidity, % RH	Ampere , A	Voltage, V	Power, W	Damper actuator LM230A-S
30	60	0.005	255	1.5	Damper open
29	60	0.005	255	1.5	Damper open
28	60	0.005	255	1.5	Damper open
27	60	0.005	255	1.5	Damper open
26	60	0.005	255	1.5	Damper open
25	60	0.005	255	1.5	Damper open
24	60	0.005	255	1.5	Damper open
23	61	0.005	100	0.5	Damper Close
22	62	0.005	100	0.5	Damper Close
21	62	0.005	100	0.5	Damper Close
22	62	0.005	100	0.5	Damper Close
23	60	0.005	255	1.5	Damper open
24	60	0.005	255	1.5	Damper open
25	61	0.005	255	1.5	Damper open
26	60	0.005	255	1.5	Damper open
27	60	0.005	100	0.5	Damper Close

3.1.2 Effects of changes temperature and humidity with a set point (25 °C and 60% RH) towards actuators

Table 9 shows values for temperature and humidity, a set point, voltage, and ampere for damper action using actuator NM24A. The set points give the actuator an order to open or close the damper. The value of the voltage and ampere of the actuator was measured using a clamp on a meter.

Table 10 shows values for temperature and humidity, a set point, voltage, and ampere for damper action using the actuator LM230A-S. The set points give the actuator an order to open or close the damper. The value of the voltage and ampere of the actuator was measured using a clamp on a meter.

Effects of changes in temperature and humidity with range-set points 23–26 °C, 55–70% RH towards actuators are different between both types. It happened because the torque values were different. The actuator movement for LM230A-S is faster than that for NM24A to open the dampers. Before the set points are achieved 25 °C and 60% RH, the actuators move to open the dampers until 25 °C, and the actuators close the dampers. This movement of close dampers happens when the temperature and humidity are low. When the temperature was increased, the dampers opened when the value reached 25 °C and closed again when the temperature decreased.

Table 9
The set points with damper actuator NM24A, 24V

Temperature, ^{0}C	Humidity, % RH	Ampere, A	Voltage, V	Power, W	Damper actuator NM24A
30	60	0.06	24.67	1.5	Damper open
29	60	0.06	24.67	1.5	Damper open
28	60	0.06	24.65	1.5	Damper open
27	60	0.06	24.64	1.5	Damper open
26	60	0.06	24.64	1.5	Damper open
25	61	0.06	3.33	0.2	Damper Close
24	61	0.06	3.33	0.2	Damper Close
23	61	0.06	3.33	0.2	Damper Close
22	62	0.06	3.33	0.2	Damper Close
21	62	0.06	3.33	0.2	Damper Close
22	62	0.06	3.33	0.2	Damper Close
23	61	0.06	3.33	0.2	Damper Close
24	61	0.06	3.33	0.2	Damper Close
25	61	0.06	24.64	1.5	Damper open

Table 10
The set points with damper actuator LM230A-S, 240V

Temperature, ^{0}C	Humidity, % RH	Ampere, A	Voltage, V	Power, W	Damper actuator LM230A-S
30	60	0.005	255	1.5	Damper open
29	60	0.005	255	1.5	Damper open
28	60	0.005	255	1.5	Damper open
27	60	0.005	255	1.5	Damper open
26	60	0.005	255	1.5	Damper open
25	61	0.005	100	0.5	Damper Close
24	61	0.005	100	0.5	Damper Close
23	61	0.005	100	0.5	Damper Close
22	62	0.005	100	0.5	Damper Close
21	62	0.005	100	0.5	Damper Close
22	62	0.005	100	0.5	Damper Close
23	61	0.005	100	0.5	Damper Close
24	61	0.005	100	0.5	Damper Close
25	61	0.005	255	1.5	Damper open

The system successfully maintained the desired temperature and humidity set points for both the two-position control and modulating control modes. In the two-position control mode, the actuators responded accurately to the fixed set points of 25°C and 60% RH. The damper opened and closed according to the preset conditions with minimal deviation. In the modulating control mode, where the set points ranged from 23–26°C and 55–70% RH, the actuators adjusted the damper positions incrementally to maintain the optimal environmental conditions. The temperature and humidity variations were consistently within a ±0.5°C and ±2% RH range from the set points, demonstrating the precision of the control system.

3.2 Energy Consumption Analysis

Figure 12 shows the energy consumption potential for damper actuators NM24A, 24V, and LM230A-S, 240V, in an office building. While Figure 13 shows the energy consumption potential for damper actuators NM24A, 24V, and LM230A-S, 240V, in an office building.

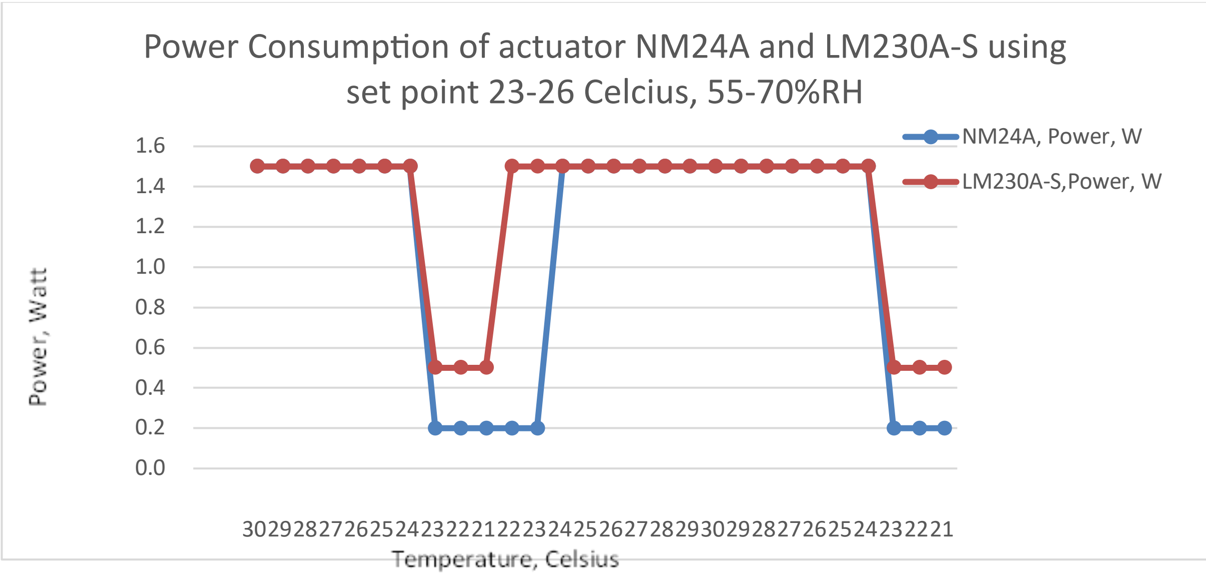


Fig. 12. Energy consumption for damper actuators NM24A and LM230A-S under optimal control conditions using range set point 23-26 Celsius and 55-70% RH and set point 23 Celsius and 60% RH

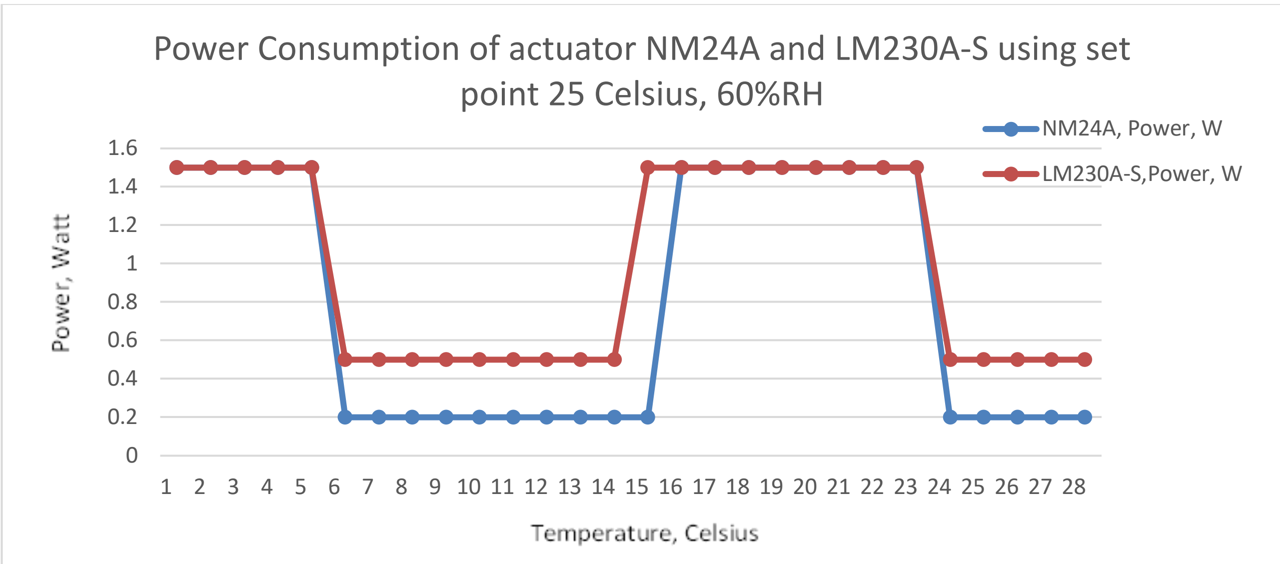


Fig. 13. Energy consumption for damper actuators NM24A and LM230A-S under optimal control conditions using range set point 23-26 Celsius and 55-70% RH and set point 23 Celsius and 60% RH

The power consumption of the NM24A and LM230A-S actuators was measured during the experimental trials. Under the two-position control mode, the NM24A actuator recorded an energy usage of 31.6 W, while the LM230A-S actuator consumed 36 W over the 3-hour testing duration. When the system operated in the modulating control mode with a set point of 25°C and 60% RH, energy consumption dropped, with the NM24A actuator using 22.5 W and the LM230A-S actuator using 28 W. The results showed a 0.87% reduction in energy consumption for the NM24A actuator and a 0.80% reduction for the LM230A-S actuator between the two control modes, highlighting the efficiency of modulating control in optimizing energy use.

3.3 Actuator Response and Efficiency

The NM24A actuator showed a somewhat slower response compared to the LM230A-S actuator, which demonstrated quicker adjustments to the damper positions. This variation in actuator responsiveness was dependent on the selected control mode. In the two-position control mode, both actuators performed well, with the dampers opening and closing based on the preset temperature and humidity set points. In the modulating control mode, the LM230A-S actuator demonstrated faster adjustments, allowing for more precise control of airflow and environmental conditions. The NM24A actuator, on the other hand, showed slower but more stable performance, which could be beneficial in systems requiring more gradual changes.

3.4 Compliance with Malaysian Standard MS1525:2014

The experimental results were also evaluated in the context of the Department of Malaysian Standard MS1525:2014 for HVAC systems. The system adhered to the recommended temperature and humidity ranges for indoor comfort, with the two-position and modulating control modes ensuring compliance with the set parameters of 23–26°C for temperature and 55–70% RH for humidity. The system demonstrated its ability to maintain comfort levels while minimizing energy consumption, fulfilling the requirements outlined in the Malaysian Standard for energy efficiency and comfort in non-residential buildings.

3.5 Comparative Analysis and Performance Evaluation

Comparative analysis between the two actuators revealed that while both types were effective in controlling the dampers, the LM230A-S actuator offered slightly better performance in terms of response time and efficiency, especially in modulating control. However, the NM24A actuator showed a marginally lower energy consumption in certain conditions, which could be beneficial in specific applications where energy savings are prioritized over response speed. The difference in energy consumption and damper movement was minimal, indicating that both actuators are viable for use in similar HVAC applications, depending on the specific needs of the system.

3.6 Limitations of the Results

While the results were promising, the study had some limitations that may affect the generalization of the findings. The experimental setup was conducted in a controlled office environment, and the results may vary in more dynamic settings with fluctuating external environmental factors. Additionally, the testing duration of three hours was relatively short, and long-term energy consumption and actuator performance over extended periods were not assessed.

Future studies should focus on longer-duration testing and a more diverse range of environmental conditions to better evaluate the scalability and efficiency of the system in different HVAC applications.

4. Conclusions

This study successfully developed and validated an IoT-based real-time control system for Variable Air Volume (VAV) air conditioning in HVAC systems. By integrating an Arduino UNO microcontroller, DHT11 temperature and humidity sensors, and Belimo damper actuators with the Node-RED platform, the system was able to effectively regulate room temperature and humidity while minimizing energy consumption. The use of two control modes two position and modulating control, demonstrated significant improvements in maintaining comfort levels, with modulating control offering greater energy efficiency. The system's performance was found to be compliant with the Malaysian Standard MS 1525:2014 for HVAC systems, highlighting its potential for deployment in the local context. The experimental results confirmed that the system could maintain set points within ±0.5°C and ±2% RH from the desired temperature and humidity, ensuring compliance with the Department of Malaysian Standard MS1525:2014 for HVAC systems. Energy consumption was reduced by approximately 0.87% for the NM24A actuator and 0.80% for the LM230A-S actuator when using the modulating control compared to the two-position control, showcasing the potential for energy optimization in HVAC applications. The study also highlighted the differences between the two actuators, with the LM230A-S actuator showing faster response times, while the NM24A actuator demonstrated slightly lower power consumption in certain conditions. Both actuators proved effective in controlling the dampers and ensuring the desired indoor climate, making them suitable for various HVAC applications.

Despite these positive findings, the study faced limitations, including the short testing duration and the controlled environment, which may not fully reflect real-world conditions. Further research is recommended to explore long-term performance, energy savings, and actuator efficiency in dynamic environments. Future studies could also consider expanding the system's capabilities to accommodate larger-scale HVAC systems, optimizing control algorithms further, and testing with more diverse environmental conditions to validate the system's applicability across various settings. In conclusion, integrating IoT technology in HVAC systems, using Node-RED and microcontroller-based controls, offers a promising approach to enhancing energy efficiency, improving indoor comfort, and ensuring compliance with industry standards. The results of this study provide valuable insights for future applications of IoT in building automation and HVAC control systems, particularly in the context of the ongoing digital transformation in the era of Industrial Revolution 4.0.

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