The Development of an IoT-based Indoor Air Monitoring System Towards Smart Energy Efficient Classroom

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Abstract—Indoor air quality has become a crucial issue, specifically during COVID 19 pandemic. The good indoor air quality will lead to occupants’ comfort condition, thus affecting their productivity. Indoor air temperature and relative humidity are two essential components of thermal comfort. This paper presents the development of a temperature and relative humidity monitoring system for the classroom using the Internet of Things (IoT). This system consists of three main components: logger nodes, a gateway logger, and an interconnected cloud server. The logger node (ESP8266/ESP32 microcontroller and DHT22 sensor) is a device at the edge of the IoT system and is placed at the monitoring location. The logger gateway is built on a Raspberry Pi 4, which serves as an intermediate server. It receives periodic data (temperature and humidity) from the logger nodes through the publish-subscribe MQTT protocol and sends it to the MongoDB Atlas cloud database. The logger gateway saves all received logs into the SQLite database as temporary local storage and then uploads the data to the MongoDB Atlas cloud at a predefined interval. The MongoDB data is then displayed on a monitoring dashboard using MongoDB charts. The recorded data has also been successfully modeled using the Gaussian Mixture Model and a simple Fuzzy model. These models can capture the dynamic of air condition in the room and predict the state of the cooling system.

Index Terms—Fuzzy Model; Gaussian Mixed Model; Internet of Things; MQTT Protocol; Sensors.

I. INTRODUCTION

Air conditioning systems are increasingly widespread for homes, office buildings, shopping centers, factories, campuses and schools. As a result, the consumption of electrical energy for the cooling system also increases from year to year. Often the use of the cooling system is inefficient due to several factors, including an adequate monitoring system is not yet available, so efficiency actions cannot be carried out optimally [1]. Instead of energy consumption issues, thermal comfort is also a crucial factor that must be achieved for a room with an air conditioning system (conditioned room) [2]. The good indoor air quality of a room will lead to the occupants’ productivity [3]. In order to achieve thermal comfort conditions, it is crucial to maintain the indoor air parameter such as temperature, relative humidity, and CO2 level of the room [4].

Currently, there are various ways to monitor the condition of the room, either manually or automatically. Air conditioning units are usually equipped with a conventional room temperature controller (thermostat), but the tools that are commonly used are usually unable to record the measured data for further analysis. In order to maintain a comfortable room temperature, the system must be able to monitor the dynamic of air condition as affected by many factors, including the weather outside (exposure to sunlight through glass windows or rain), room occupancy rate, time of day (morning, afternoon or evening) and the impact of heat generated by electronic equipment [5], [6].

An Internet of Things (IoT) is a device connected through the Internet network so that it can be monitored and controlled remotely as long as an Internet network is available. This IoT technology is relatively affordable and quite easy to implement so that its use has been included in the daily activities of various industries; its application includes and is not limited to smart city applications [7], [8], smart campuses [9]–[11], smart grid, smart home [12], security [13] and smart building management system [14], [15]. There has been no standard as a reference in the application of IoT in the field of building management, so there are still plenty of opportunities for exploration of various methods and related technologies [16]. This study aims to develop a temperature and humidity monitoring system for classrooms based on the Internet of Things which offers more comprehensive measurements and broader
coverage areas. The first stage of this research was to
design the IoT-based monitoring system architecture.
The development of this system was then continued by
testing two IoT loggers: one to monitor indoor air
conditions and the other to monitor outdoor air
conditions. Prior to field testing, the two IoT loggers
were adjusted so that the measurement results of the
two loggers were identical when measuring the same air
condition. The adjusted measurement was modelled
linearly using the least-squares method. The saved data
was then analysed and used to build a simple model
using GaussianMixture and Fuzzy approaches to
capture the dynamic of air condition as it is influenced
by the outdoor weather and the air cooling system.

II. METHODOLOGY

The development of this IoT-based
temperature/humidity monitoring system includes the
design of the IoT system architecture, the setup of the
MongoDB database in the Atlas cloud, the
development of a dashboard monitoring system using
MongoDB Charts, and the process of calibrating the
sensors.

A. IoT Architecture System

In general, this IoT-based temperature/humidity
monitoring system consists of three main components:
(1) logger nodes, (2) logger gateways, and (3) cloud
servers that are connected to each other as described in
Figure 1.

![Fig. 1. IoT-based monitoring system architecture](image1)

The logger node is the far end device of the IoT
system and is placed at the monitoring location. In this
study, the logger device is composed of the ESP8266 /
ESP32 microcontroller family is equipped with Wi-Fi
connectivity and paired with a DHT-22 temperature and
humidity sensor. The logger is connected via a local
WLAN network (Wi-Fi technology) with the logger
gateway. This local WLAN can be an ad-hoc network
created by a logger gateway or a WLAN network
originating from a public Wi-Fi router device.

The logger gateway is a Raspberry Pi 4, which functions as an intermediary server, which receives
periodic temperature and humidity data from the logger
node, and sends it to the MongoDB Atlas cloud
database, which will be discussed in more detail later.
Communication between the logger gateway and logger
node is carried out through the publish-subscribe
MQTT [17] protocol, where the logger node unit
becomes the MQTT client and the logger gateway
become the MQTT broker as well as the MQTT client.
Communication between the logger gateway to the
MongoDB Atlas is done via the MongoDB wire
protocol over the TCP/IP standard socket connection.
The intermediary server function in this research is
designed in two versions, namely: NodeJS and Python
script.

The query-driven communication flow between the
logger gateway and the node can be seen in Figure 2.
Two MQTT communication channels were provided,
namely the 'control' channel and the 'log/data' channel.
The logger gateway periodically (every 10 minutes in
this study) sends a message to the 'control' channel,
which will be received by all logger nodes. When
receiving the control message, the logger node will
respond by sending a message containing the loggerID
and the current temperature/humidity to the 'log/data'
channel.

![Fig. 2. The query-driven communication flow between logger
gateway and node](image2)

The use of these two separate channels is carried out
with the following considerations:

1) Security

When the system has been implemented with
loggers on a large scale, the 'control' channel can
be opened to the public so that all devices can join
the channel to get information about when
temperature and humidity logging should be
carried out, or for development other more complex
control schemes (including initiation when a new
logger joins the network for the first time).
Meanwhile, information regarding the 'log/data'
channel can be provided only for 'trusted' loggers,
so those other unverified devices cannot send fake
logging info because they cannot access the
'log/data’ channel. This scheme can be further
developed so that the information dissemination
process regarding the 'log/data’ channel is
integrated with the authentication process. For
example, the logger can be registered with the
system via a management dashboard. A secret
'log/data’ channel and access token are provided by
the dashboard upon successful registration. The logger then can access the given MQTT channel while providing access token [18]. This schematic is described in Figure 3.

2) Efficiency

Similar to the first point, a system that is implemented on a large scale will result in a large number of MQTT message transactions as well. If only one channel is used both for 'control' and 'log/data', control commands from the logger gateway will be mixed with data logging messages from the logger node. As a result, it will cause unnecessary processing on the logger node side [19]. In operation, the logger node must monitor the communication channel to get commands from the logger gateway, which in this study is the command to do logging. If the command is mixed with messages containing logging data from other nodes (a large number), then each node must filter the incoming messages only to recognize control messages from the gateway logger, thus affecting performance. Processing this large amount of messages may not be a problem for devices with more resources, but it can have an impact on microcontroller devices.

### B. MongoDB Atlas

The measurement data of several loggers is stored in a MongoDB database provided by MongoDB Atlas. MongoDB Atlas is a global cloud database service for modern applications [20]. Unpaid service is available with limited 512 MB storage capacity, sharing RAM, Highly available replica sets (provided three nodes), end-to-end encryption, automatic patches, and REST API.

The data stored in the MongoDB database is loggerID, timestamp (ts), temperature (temp) and relative humidity (hum) in JSON format (JavaScript Object Notation) as shown in Figure 4.

```json
{
  "_id": {
    "$oid": "605366675e8b6713a449066"
  },
  "loggerID": "loggerA",
  "ts": {
    "$date": {
      "$numberLong": "161607369494"}
  },
  "temp": {
    "$numberDouble": "29.4"
  },
  "hum": {
    "$numberDouble": "52.2"
  }
}
```

Fig. 4. A sample document from the MongoDB database

The MongoDB database automatically adds a unique identity _id for every record saved. Figure 5 shows an overview of the data stored in a MongoDB database. The report is based on a sample of 1000 documents. The total amount of data stored is 5925. The two loggerIDs are logger3 and logger4. The recorded air temperature was in the range of 27.7°C to 36.2°C with an average temperature of about 30°C and a skew-normal distribution with a long tail on the right side. Air humidity is in the range of 35.9%RH to 87.5%RH and it can be seen that there are two peaks of data distribution (local and global maximum) so it can be concluded that the data distribution is bi-modal. Data stored in the database were in the period from 5 to 26 November 2020.

<table>
<thead>
<tr>
<th>Control</th>
<th>logger node</th>
<th>Channel 'control'</th>
<th>Channel 'log/data'</th>
<th>Logger permits</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>logger3</td>
<td>Control: publish</td>
<td>Control: publish</td>
<td>Permissions:</td>
</tr>
<tr>
<td>2</td>
<td>logger4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>logger5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>logger6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>logger7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>logger8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3. Data transmission security scheme using 'control' and 'log/data' channels

The gateway logger then saves all received logs into an SQLite database as temporary local storage before being uploaded to the MongoDB Atlas cloud. In this research, we create two schemes related to local storage. We have tested both storage schemes, and both are working fine.

1) All log data received via MQTT is stored in the SQLite database first and will be uploaded to the MongoDB Atlas cloud at specified periods (if internet connection exists).

2) All log data received via MQTT will be directly uploaded to the MongoDB Atlas cloud. If during upload there is an interruption in the internet connection, the logs that failed to upload will be stored in the SQLite database first, and try to be uploaded again in the next logging period (10 minutes later) together with the new data.
C. MongoDB Chart

MongoDB charts are tools to visualise data in MongoDB Atlas. There are various types of charts available such as column/bar charts, line/area charts, combo charts, grid charts (heatmap and scatter), circular charts (donut and gauge), text charts (number, word cloud and top item), and geospatial charts (heatmap, scatter and choropleth). It is easy to create a dashboard with a collection of charts using MongoDB charts. Charts update automatically as real-time data comes into the MongoDB database. The dashboard is updated in real-time and can be made interactive by enabling filters.

D. DHT22 Sensor Adjustment

Two IoT loggers equipped with DHT22 temperature/humidity sensors generated different reading measurements when placed in the same room, so an adjustment process was required for both sensors. The process was carried out in a room equipped with air conditioning and windows so that it could condition a reasonably wide range of temperature and humidity. One of the DHT22 sensors will be used as a reference, for example, the sensor used in the loggerB. Under ideal conditions, a calibrated temperature/humidity sensor can be used as a reference.

The data from the temperature and humidity measurement during the adjustment process on two DHT22 sensors can be seen in Figure 7. The process was carried out from 8.10 pm local time on 18 March 2021 until the morning at 9.00 am on 19 March 2021.

Figure 7 shows that there is a difference between loggerA and loggerB in both temperature and humidity measurements. There is a fairly large gap (about 5%) seen in the results of air humidity measurements. The adjustment process was performed using the DHT22 sensor on the loggerB as a reference. The result of linear modelling for air temperature on loggerA is given in the following linear equation:

\[ t_{\text{adjusted}} = 0.93 \times t_{\text{measured}} + 1.91 \]  

Figure 7 shows the dashboard of the air condition monitoring system. The dashboard shows the current measured humidity and temperature as gauge charts. It also shows the historical measurements of humidity and temperature as line charts.
After adjusting the loggerA, the plot results for the same period can be seen in Figure 10. The results of temperature and humidity measurements during the adjustment process show that temperature and humidity measurements with loggerA and loggerB almost overlap in one plot. It indicates that loggerA and loggerB have been successfully "calibrated" so that both loggers are ready to use.

![Fig. 8. The results of fitting air temperature data from loggerA and loggerB](image)

Where $t_{\text{adjusted}}$ is the result of temperature measurement on loggerA that has been adjusted and $t_{\text{measured}}$ is the original result of temperature measurement on loggerA. This linear model is the result of fitting with the least-squares method on the measurement data, which is displayed as a scatter plot as shown in Figure 8.

Linear modelling was also carried out on the loggerA humidity measurement with the results in the form of the following linear equation:

$$h_{\text{adjusted}} = 0.98 \times h_{\text{measured}} - 5.06 \quad (2)$$

where $h_{\text{adjusted}}$ is the result of measuring humidity on an adjusted loggerA and $h_{\text{measured}}$ is the original result of measuring humidity on the loggerA. This modelling is the result of fitting with the least-squares method on the measurement data and displayed as a scatter plot as shown in Figure 8.

![Fig. 9. The results of fitting air humidity data from loggerA and loggerB](image)

Table 1 shows the parameters and metrics of the regression models for temperature and relative humidity. A high correlation value (0.975656) for the temperature model indicates that the modelling results have high accuracy; in other words, the results of air temperature measurements with adjusted loggerA and loggerB are almost identical.

![Fig. 10. The results of monitoring the temperature and humidity of the air after the adjustment process](image)

| TABLE I. THE PARAMETERS AND METRICS OF THE FITTED LINEAR MODELS (TEMPERATURE AND RELATIVE HUMIDITY) |
|---------------------------------------------------------------|-----------------|-----------------|
| Parameters of Regression Model                                | Temperature     | Relative Humidity |
| Slope                                                        | 0.92596934      | 0.982           |
| Intercept                                                    | 1.91308973      | -5.06556        |
| Metrics of Regression Model                                  |                 |                 |
| RMS error                                                    | 0.006698        | 0.042672        |
| R2 score                                                     | 0.975656        | 0.99985         |

III. RESULT AND DISCUSSION

The developed system has been successfully applied to monitor air conditions in the field. The system is ready to monitor the temperature/humidity of the air in an enclosed space and an open space. The data collected from the monitoring system is used to model the dynamic of air condition due to the outdoor weather condition and the effects of a cooling system.

A. Experimental Testing

Air temperature and humidity measurements were conducted at two locations: indoor and outdoor...
environments. The first location was a classroom. The loggerA and a mini server (Raspberry Pi 4) were placed in this classroom. LoggerA functioned to record the indoor air temperature and humidity. The second location was a corridor with considerable access to fresh air. The loggerB was located in this corridor. LoggerB served to monitor the outdoor air condition. The measurements began at around 11 am on 19 March 2021.

Monitoring of air conditions was carried out for six days consecutively, starting from 20 March 2021 to 25 March 2021 as seen in Figure 11. The air conditioning system was only turned on (as indicated by the value of the state equal to 1) for a few hours on 24 and 25 March 2021 specifically for this monitoring purpose. The air conditioning system is usually turned on when there is a class session in progress. However, there have been no classes scheduled in the building for almost two years due to the pandemic. When the cooling system was turned off, the temperature and humidity in the classrooms were relatively stable (a temperature range of about 28°C and a humidity of about 70% RH). The outdoor air conditions are pretty extreme, namely: the air temperature range is between 24°C to 33°C, and the humidity range is between 50%RH to 100%RH.

When the air conditioning system was turned on, the air temperature quickly dropped to a range of 24°C when the outdoor temperature was in the range of 30°C. A decrease also occurred in the humidity in the classroom from the range of 75%RH to the range of 60%RH when the outdoor humidity was in the range of 90-90%RH.

The air condition in the classroom is relatively stable and isolated from the outdoor air condition because the building is equipped with a double skin facade and a heat-insulating wall that can regulate the intensity of light and reduce the heat from the sun that enters the room so that the room is bright enough and cool even when the air conditioner is turned off.

**B. Modeling Results**

The logged data were analyzed to understand the relationship between indoor and outdoor temperature/humidity and the effect of the cooling system on indoor air conditions. The distribution of temperature and humidity parameter values in each logger provides an overview of the distribution of each of these parameters.
Figure 13(b) clearly shows that there are two peaks (local and global) in the humidity data from loggerA. If we fit two Gaussian distributions on the data using the ExpectationMaximization [21] algorithm, we will get two clusters with the following distribution:

- Gaussian distribution in low humidity cluster with $\mu = 68$, $\sigma = 5.2$, weight = 0.3.
- Gaussian distribution in high humidity cluster with $\mu = 75$, $\sigma = 1.1$, weight = 0.7.

The mean values of the low and high humidity clusters are 68%RH and 75%RH. The peak at the high humidity cluster is much higher than the peak at the low humidity cluster because during the monitoring process, the air conditioning system is turned on for a minimal time compared to the length of the measurement.

The data obtained can be used to predict the state of the cooling system: actively working or not. This model can be used to monitor unmeasured or hidden variables. It can be a cheaper and more effective solution than installing a current sensor in the air conditioning system.

IV. CONCLUSION

A temperature and relative humidity monitoring system for a conditioned classroom using the Internet of Things has been developed. The system has been successfully "calibrated" and tested to simultaneously monitor indoor and outdoor air conditions. The monitoring results have been analyzed and used to construct a Gaussian-Mixture and a simple fuzzy model capturing the relationship between the indoor air conditions and the state of the air conditioning system. Further research can use the model as an input to a controller of the air conditioning system to achieve its optimal operation.

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