Developing an IoT-Based Control System for Existing Air Conditioner using MEMS

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Abstract. Caused by the energy revolution, energy saving becomes a bigger topic than ever. This paper is about the developing of a new controlling system for air conditioning, which could save up to 66% of the energy consumed.

1. Introduction
The air conditioning branch is one of the biggest energy consumers of our planet. Developing a new controlling system based on in ISO 7730 [1] described Predictive Mean Vote (PMV) procedure, could help the existing air conditioners to become more energy efficient. Human thermal comfort as also described in ISO 7730 cannot be expressed by the temperature only. Humidity, air velocity and radiation heat affect the zone of comfort as well as the temperature does. The developed controlling circuit realized on a breadboard ensures to measure these influences by using microelectromechanical sensors (MEMS) and to calculate the measured parameters into simple data which can be sent wireless to the air conditioner itself. Being managed using a smartphone application and simply telling the phone how you feel e.g. cool or normal, the air conditioner would not simply cool till you freeze, it would perfectly stay in your zone of comfort, meanwhile saving up a lot of energy.

2. Basics
Air-conditioning systems as they are used today, mostly regulate room climate only by setting the temperature. Human beings sense for temperature is actually a combination of air velocity, humidity and temperature. So the area of wellbeing can be reached by regulating either of those three. This area of comfort is described in the ISO 7730; measurement regulations are set in the ISO 7726 [1] [2].

2.1. ISO 7730
ISO 7730 presents methods predicting the general thermal sensation and degree of discomfort of people exposed to moderate thermal environments. A human being’s comfort zone is mainly related to the thermal balance of the whole body. This balance is influenced by several parameters that could contribute towards human thermal comfort, which includes physiological condition like clothing and activity of human, as well as the environmental parameters like temperature, humidity and air velocity [3]. Once these factors have been measured, the local thermal comfort could be predicted through ISO 7730 by calculating the Predicted Mean vote (PMV). The PMV predicts the mean value of the votes of a large group of people on the ISO thermal sensation scale (+3 = hot; +2 = warm; +1 = slightly warm; 0 = neutral; -1 = slightly cool; -2 = cool; -3 = cold).
The ISO 7730 also establishes the time interval the sensors need to measure data. Table 1 shows temperature, humidity and air velocity need to get measured every second. To get an average air velocity the mean over three minutes needs to get calculated. This is needed to calculate also the standard deviation of the velocity to calculate the turbulence value, necessary for further calculating the PMV.

| Value             | Type   | Time interval       |
|-------------------|--------|---------------------|
| Temperature       | Measured | As fast as possible * |
| Relative Humidity | Measured | As fast as possible * |
| Air velocity      | Measured | Minimum 0.5 s |
|                   |         | Ideal 0.2 s *       |
| Mean air velocity | Calculated | 3 min + |
| Turbulence        | Calculated | 3 min + |

*ISO 7730 [1], *ISO 7726[2]

2.2. ISO 7726
This standard specifies the characteristics of instruments for measuring physical quantities characterizing an environment as well as the methods for measuring these physical quantities, as in Table 2. The sensors selected needs to for fill the requirements set in ISO 7726.

| Value            | Range     | Error     |
|------------------|-----------|-----------|
| Air temperature  | 10 – 40 °C| +/- 0.5 °C|
| Air velocity     | 0.05 – 1 m/s | +/- 0.05 m/s |
| Humidity         | 0.5 – 3 kPa | +/- 0.15 kPa |

2.3. Energy
Comparing the usual operating point of an air conditioner, which means high cooling and high ventilation, to the operating point using the knowledge of ISO 7730[1], a maximum of 2/3 of the power consumed can be saved. By taking the ISO 7730 guidelines and the power consumption of the fan and refrigerator compressor into a graph a new operating field is generated, as shown in Figure 1. As can be seen here, the same comfort can be generated by only 700W (600W compressor + 100W fan) compared to originally 2100W (2000W compressor + 100W fan) which is a massive save of energy. This resolves in ventilating as much as possible and cooling only if necessary, as the fan only takes 1/20 of the power the compressor needs in full power mode. Ventilating the air, depending on the relative humidity and comfortability, can be achieved at higher temperatures and less energy will be consumed. The worst operating point using the IS0 7730 is at 2050W (2000W compressor + 50W fan) but still 50W less than the usual operating point.
2.4. Air velocity

To measure the air velocity vector, in principle a 3-dimensinal sensor is needed. As the device will be placed right on the wall, all 3-dimension need not to be measured, because air flowing straight onto the wall will be slowed down by the wall itself to zero. Therefore, a 2-dimensional sensor will do. Furthermore, the dimensional aspect the sensor needs to fit into the guidelines of ISO 7730 as well as ISO 7726.

The selected sensor is the FS7 manufactured in Switzerland by a company specialized in MEMS technology, named IST-AG as seen in Figure 2.

Comparing the technical dates of the FS7 (Table 3) to the guidelines set in ISO 7726 (Table 1), the sensor fits right into the ISO. As the sensor is part of the MEMS (micro electro mechanic system) family the entire sensor is very small, which is also required since the plan is to keep the device as small as possible. The biggest advantage of using a MEMS sensor is that the small sized materials got a very small thermal mass and therefore reacts quickly to changes in temperature.

The ground plate of the FS7 is made out of a ceramic substrate, and then a thin platinum layer is added. Using a digital Microscope (refer to Figure 3), the platinum heater resistor (RH = 45 Ohm) that
actually senses the airflow shows up not to be squared as it would be preferred. It measures 1.27 x 1.06 mm². That is why airflow from different angles is expected to vary in the result.

**Table 3. Technical dates FS7**

| Range           | 0m/s – 100m/s |
|-----------------|---------------|
| Sensitivity     | 0.01m/s       |
| Accuracy        | 3% of measured value |
| Temperature     | -20°C - 150°C |
| Temperature sensitivity | < 0.1 %/K |
| Heater: RH      | 45 Ohm        |
| Temperature sensor RS | 1200 Ohm    |
| Size            | 0.2 x 2.4 x 6.9 mm |

**Figure 3. Microscope picture of FS7**

Flow sensors are based on the relation of the flow speed to the heat transferred by convection. As flow passes across the heated sensor area, heat is carried away from the heater area by the medium. As flow increases, so does the amount of heat that is transferred. In the Constant Temperature Anemometer (CTA)-Mode a constant temperature difference between the heater and the temperature sensor can be achieved by adapting a Wheatstone-bridge, as seen in Figure 4.

**Figure 4. Circuit of FS7 evaluation board for FS5**
In that bridge circuit the supplied electrical power controlling the temperature difference is a function of the flow speed. That power is converted into a voltage output signal to be readout easily. The medium temperature variation is measured by the temperature sensor on chip (RS = Pt1200). The resistors R1 to R6 can be chosen as shown in Figure 4. By resistor R1 the temperature difference between heater (RH) and medium (RS) is set to \( DT = 30 \) K for air. The resistor R2 should be adjustable within \( \pm 10 \% \) for calibration [4].

2.5. FS5 Evaluations board

Originally designed for the FS5 sensor, which is the predecessor of the FS7, the flow module also works with the FS7, because the resistors RH and RS of the FS7 and FS5 got the same values (Table 3, Table 4).

| Time response                  | < 100ms |
|--------------------------------|---------|
| Temperature range              | 0 – 80°C|
| Heater RH                      | 45 Ohm +/- 1% |
| Temperature sensor RS          | 1200 Ohm +/- 1% |
| Power supply                   | 5 VDC +/- 5% |
| Supply current                 | 90 mA   |
| Analogue output, nonlinear     | 0 – 10 V|

2.6. Relative humidity and temperature

In this work, a DHT22 sensor is used to measure the temperature and the relative humidity (Figure 5). It is calibrated und uses digital signal technology to ensure reliability and stability while consuming less power [5]. Features such as high precision, small size, speedy response time und low-costs make the DHT22 sensor as the best choice in comparison to DHT11 and SHT75 (Table 5).

| Model                   | DHT22 | DHT11 | SHT75          |
|-------------------------|-------|-------|----------------|
| Humidity Range          | 0 – 100 % | 20 – 80 % | 0 – 100 %          |
| Temperature Range       | -40 – 80 °C | 0 – 50 °C | -40 – 123.8 °C |
| Accuracy                | ± 2 – 5 % (Humidity) | ± 5 % (Humidity) | ± 1.8 % (Humidity) |
|                         | ± 0.5 °C (Temp) | ± 2 °C (Temp) | ± 0.3 °C (Temp) |
| Repeatability           | ± 0.3 % (Humidity) | ± 1 % (Humidity) | ± 0.1 % (Humidity) |
|                         | ± 0.2 °C (Temp) | ± 1 °C (Temp) | ± 0.1 °C (Temp) |
| Operating Voltage       | 3 - 5 V | 3 - 5 V | 2.4 – 5.5 V      |
| Response time           | Average | Average | 8 s (Humidity)      |
|                         | 2 s     | 2 s     | 5 to 30 s (Temp)   |
| Output signal           | digital signal | digital signal | digital signal    |
| Price                   | 3 - 9 € | 1.5 - 5 € | 30 - 45 €         |

The DHT22 consist of a capacitor-based humidity sensor and a NTC temperature sensor (thermistor). The capacitive sensor has two electrodes separated by a dielectric material.
Figure 5. Electrical connection diagram of DHT22

Its dielectric constant changes with humidity, and accordingly the capacitance does so. This change is measured and processed by the chip so that it can be read out by a microcontroller. The thermistor is made by sintering semiconductor materials such as ceramics or polymers to achieve greater resistance change with low temperature change.

The communication between DHT22 and microcontroller is made through a one-wire bus from the company MaxDetect. The microcontroller receives from the sensor 40 bits: 16 bits of 10 times relative humidity value + 16 bits of 10 times temperature value + 8 check-sum bits [6].

If the data is transmitted correctly, then check-sum should be the binary sum of the both 16-bit data. The following example demonstrates the conversion from the 40 data bits to temperature and humidity values:

After measuring a temperature of 26.9°C and a relative humidity of 52.1% the sensor sends the following 40 bits string:
0000 0010 0000 1001 0000 0001 0000 1101 0001 1001

- Relative humidity RH calculation:
  binary = 0000 0010 0000 1001
  -> decimal = 521 = 10 × RH in %
  => RH = 521/10 = 52.1%

- Temperature calculation:
  binary = 0000 0001 0000 1101
  -> decimal = 269 = 10 × T °C
  => T = 269/10 = 26.9°C

- Check-sum calculation:
  Check-sum = 0000 0010 + 0000 1001 + 0000 0001 + 0000 1101 = 0001 1001

2.7. ESP32 Microcontroller

The ESP32 of the company Espressif has been selected as controller of our system [7]. The ESP32 is the updated version of the ESP8266. Bluetooth and Wifi were added to the board. It is low-cost, low-power system on chip series of microcontrollers with WiFi and Bluetooth capabilities. Comparing this to other development boards on the market e.g. Arduinos, the ESP32 costs only half of them. It is designed for wearable electronics and internet of things applications. The ESP32 turned out as a reliable option in an industrial environment because of the wide operating temperature range and the multiple input pins [8]. One of the main reasons for choosing the ESP32 except the price and the WiFi module was the built in analog digital converter (ADC), knowing that FS7 combined with the evaluation board gives an analog output that needs to be converted into bits. Moreover, the ESP32 has a built in low-power mode, which is useful when the device is later placed into installation housing. Therefore, the device needs to be operated using a battery, where the low power mode promises an extended operating time.
3. Wiring
In the proposed system the temperature and the relative humidity will be measured through DHT22. The voltage supply of the sensor must be between 3.3 and 6 V (recommended 5 V). The DHT22 data pin is related to the digital pin GPIO4 of the ESP32 microcontroller board. The data queue between DHT22 and ESP32 must be related by the pullup-resistor of 10kΩ. Figure 6 shows the overall setup.

**Figure 6a.** Block diagram of measurement setup

![Figure 6a](image-url)

**Figure 6b:** Device mounted on a bread board

![Figure 6b](image-url)

**Figure 6c:** Measuring components wiring plan

![Figure 6c](image-url)
For powering the evaluation board a parallel connection to the USB power supply is needed, which ensures a constant 5V power to the evaluation board. Powering the evaluation board through the ESP32, which comes with a built in 5V output-pin VIN, did not work properly, because a pull-up diode in line between USB power in- and 5V output-pins results in a 0.4V loss.

The evaluation board for the FS7-velocity sensor is connected to the ESP32 built in analog-digital-converter input-pin GPIO36. To restrict the input-voltage to the maximum allowed value of 3.3V, a 3.9 k Ohm to 4.7 k Ohm voltage divider is set between them. The ESP32 microcontroller is connected to a webserver that is used to display the results of the measuring.

4. Software

4.1. FS7 Linearization

A challenge occurs programming a sketch (name of an arduino based program) that outputs the right airspeed in m/s because the analog input into the Analog-Digital-Converter of the ESP-32 is not linear, as seen in Figure 7, thus one cannot just scale them up easily.

![Figure 7. Dependence of FS7 output-voltage on airspeed](image)

For linearization one needs to get three measurement points at 0 m/s airspeed, 0.5 m/s and max airspeed of 1 m/s (Figure 7). By using the CTA-formula for the FS7 anemometer with voltage \( U_0 = 3.6 \) V at a zero velocity, one can solve the equation system to get the unknown variables \( k \) and \( n \):

\[
U_V = 3.6V \times \sqrt{1 + k \times V^n}
\]

Subsequently one can apply this formula to convert voltages to the life airspeeds. The variables are simply set fix in the program and only need to be changed if the precise measurement range is changed from 0-1 m/s to another. This process is included into the sketch and is completed every second for each value measured [4].

\[
\dot{V} = \frac{[(U - U_0) - (U + U_0)]^{\frac{1}{n}}}{(k^{\frac{2}{n}}) \cdot U_0^{\frac{2}{n}}}
\]

4.2. PMV

The Predictive Mean Vote (PMV)-parameter is based on a scientist’s study written down in ISO 7730 to show the thermal comfort zone of humans. Every human is different so is the comfort zone, that is why the Predicted Percentage of Dissatisfied (PPD) measured in percent never gets down to zero but
stops at 5%. The PPD shows how many people are dissatisfied at the current PMV value. PMV ranges from -3 up to 3 (Figure 8), but the comfort zone described in ISO 7730 is between -0.5 and 0.5, where no more than 10% feel dissatisfied. Further down the scale people start to feel colder and further up more and more people start to feel warmer.

![Figure 8. PMV and PPD](image)

For calculation of the PMV value a lot of different variables are needed (Figure 9) to get the right result. Most of them can be measured live with the device designed such as air temperature, air velocity and relative humidity. Turbulence must be calculated from mean air velocity $v_m$ and standard deviation $\sigma_v$ of air velocity:

$$Turbulence = \frac{\sigma_v}{v_m}$$

Other parameters can’t easily be measured and must be preset depending on the level of activity of the person or the insulation by the clothes the person is wearing (Table 6, Table 7).

![Figure 9. Parameters influencing PMV](image)

ISO 7730 describes the energy consumption of a human depending on different activities. Basically, one has to change the value of energy consumption for the PMV calculation every time depending on people’s activity. In the program described here its value is fixed to 58 W/m² for a human sitting relaxed. This equals 1 met (Metabolic equivalent).
Table 6. Power emission for a human and its metabolic equivalent (ISO 7730) [1]

| Activity                  | W/m² | met | W*  |
|---------------------------|------|-----|-----|
| Ajar                      | 46   | 0,8 | 83  |
| Sitting, relaxed          | 58   | 1,0 | 104 |
| Sitting, working          | 70   | 1,2 | 126 |
| Standing, easy work       | 93   | 1,6 | 167 |
| Standing, hard work       | 116  | 2,0 | 209 |
| Walking, flat ground 2 km/h | 110  | 1,9 | 198 |
| Walking, flat ground 4 km/h | 165  | 2,8 | 297 |

*heat emission calculated with average skin area of 1.8m² for human

Not only activities do make one feel warm, different heat resistances of clothing also do. The clothing isolation factor measured in [clo] needs to be preset for the PMV calculation. Like the power consumption this factor needs to be adopted depending on the clothes wearing. In this work it is preset to 1 clo = 0,155 m²*K/W [10] which equals wearing t-shirt and trousers, socks, shoes and underwear (Table 7).

Table 7. Clothing-Isolation [9]

| Clothing | Isolation in clo | Change of operating temperature in K |
|----------|-----------------|-------------------------------------|
| Slip     | 0.03            | 0.2                                 |
| T-Shirt  | 0.09            | 0.6                                 |
| Shirt    | 0.25            | 1.6                                 |
| Shorts   | 0.06            | 0.4                                 |
| Pullover | 0.28            | 1.7                                 |
| Jacket   | 0.35            | 2.2                                 |
| Trousers | 0.25            | 1.6                                 |
| Skirt    | 0.15            | 0.9                                 |

5. Calibration
For the first operation test after wiring and programming a wind tunnel was used. Important before getting the values for airspeed is to set the analog output voltage of the evaluation board to $U_0 = 3.6$ V at 0 m/s airspeed, by the potentiometer (R17 = 500 Ohm) built on the evaluation board itself (Figure 4). To ensure 0 m/s the FS7 was covered by a small box turned upside down and the voltage was measured by a Fluke F15B multimeter. After setting the zero voltage the device was placed into the air tunnel and the airspeed was set up to the two other points needed for the linearization, described in Section 4. For reference measurements an air velocity meter VelociCalc 8384[10] was used. During the calibration the device was connected to the computer via micro USB-connector and the digital values were read out by the com window, a tool to display the microcontroller doings.

6. Function
6.1. Test
After calibrating the system, the entire device was placed in thermally different areas to test the system on the edges of the operating field, such in a refrigerator, outside on a windy day and directly in the sun. As to see on the results (Figure 10) given the device works just fine.
The challenge was that the exact PMV value can only be checked using an expensive reference room comfort measurement device such as testo 400 Comfort-set [11]. In this work PMV values could only be estimated roughly by the team’s personal feelings. To test the 3-dimensional behavior the bread board was again placed into the wind tunnel. The orientation of the sensor was changed during the different tests, so that all three dimensions could be checked. The result of the 3D test was as expected, that the orientation does only affect the air-velocity measuring neither the humidity nor the temperature.

As the FS7 measures airspeed using a rectangle heater plate to measure heat loss, air coming towards it from the X or Y axis should take different amounts of heat from it. In reality the impact of the rectangular heater can’t be confirmed. Both directions got the same effect. That might be understood because the surface area is equal in size in either direction and as it is for the convected thermal mass. Wind coming from the Z axis does have a different behavior, it can’t just flow across the sensor, but gets stopped to zero by it and pushed into X and Y axis.

6.2. Displaying data

The ESP32 was connected to an integrated webserver running on it, responsible for returning a webpage to the client when the client is connected to it through HTTP (Hypertext Transfer Protocol). The sensor data could be shown on the webpage using a mobile device by connecting it to the local webserver by a local Wi-Fi. In detail, after creating the webserver with the microcontroller, the ESP32 must be connected to the Wi-Fi network, and then an IP address of the ESP32 in the local network will be shown on the Arduino serial monitor. When this IP address will be typed in, the browser will send a request to the webserver for connection. After the connection is established, the webserver will return a webpage which sends requests automatically to the webserver to update the sensors values in their placeholder every 2 seconds.

Figure 11. Communication between the webserver and the webpage

The temperature, humidity and air velocity reading from DHT22 and FS7 sensors are displayed in two forms on the webpage. In the first part of the webpage the actual data reading of the sensors are
displayed (Figure 11) and in the second part three charts are created which could display a maximum of 40 data points (Figures 12). In this work an asynchronous HTTP webserver has been created allowing updating the sensors data reading automatically without the need of refreshing the webpage.

7. Outlook
A prototype device is designed and built on a bread board to measure and control a comfort climate according to ISO 7730 collecting temperature, relative humidity and air velocity data. Being able to display the room climate on any internet capable device the first steps towards the goal of fully functional air condition control are made. In future work and cooperation with the Universiti Malaysia Perlis (UniMAP) the program and the sensor system will be further customized so that a connection to an existing air-conditioner can be made.

![Temperature chart](image1)

**Figure 12a. Temperature chart**

![Relative humidity chart](image2)

**Figure 12b. Relative humidity chart**

![Air velocity chart](image3)

**Figure 12c. Air velocity chart**

Further via webserver one cannot only display data but also will be able to control the system over internet. At a final step the entire circuit will be redesigned to a smaller and more compact solution, all built together in an installation housing. At this point one will be able to connect multiple devices to the cloud to collect climate data from different locations in the rooms and perfectly operate an air conditioner (Figure 13). Multiple air conditioners can be controlled by only using a mobile or laptop. In the latest step of the project the cloud could be equipped with an artificial intelligence system to get one’s thermal comfort self-controlled. The artificial intelligence would also make the most efficient use of the energy available. Trying to set new standards in efficiency of air conditioners the team aims to design a low budget version of the final device to spread it all over the world to take over responsibility in saving energy.
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Figure 13. An IoT-Based Smart Co