DEVELOPMENT OF AN OPEN SOURCE AIR POLLUTION MONITORING SYSTEM

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2. Acknowledgements

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3. Abstract

Air pollution has been steadily increasing over recent decades due to a number of factors such as industrialisation, urbanisation, population growth. This increase is causing detrimental health effects and is harming the environment. Therefore, air pollution must be monitored and controlled to negate these negative effects. In order to monitor air pollution in a surrounding area, two Internet of Things (IoT) based air pollution monitoring systems have been designed and tested to monitor temperature, humidity, pressure, and volatile organic compounds (VOCs). These two systems use a Bosch Sensortec BME680 air quality sensor to monitor the data and contain an Adafruit SSD1306 OLED display to show the information to the user. Both systems use an Mbed NXP LPC1768 as the microprocessor. One of the systems displays live results, obtained from the BME680 sensor, on the OLED display. The second prototype records one measurement for each variable every minute and stores these in an SQL database. This system can be used to monitor the air quality of the surrounding area for upwards of 24 hours consecutively. The data is sent from the Mbed to the database via an Ethernet connection. A desktop application has been developed which can read from the database to plot graphs over a custom time range, generate statistics for the data, and export the data in a CSV format. These systems have been designed such that they are cost efficient and use free and open-source software. This means that anyone with a fundamental understanding of electronics and programming can easily build these air pollution monitoring systems and customise them to fit their own requirements.

Contents

4. Introduction

Over the course of the past few decades, air pollution has become a significant problem on an international level. The quality of air has reduced as international transport has increased and countries become more industrialised, urbanised, and grown in population.

The short and long term impacts of air pollution on the environment and human health has been the subject of numerous pieces of research due to the increasing awareness of modern society [1]. From decades of research, it has been discovered that 40,000 people per year in the UK [2] and 4.2 million people per year around the world die prematurely due to air pollution [3]. It has also been found that air pollution has a number of environmental impacts. One of the main environmental impacts is that air pollution causes acid rain to occur. Acid rain can cause limestone and marble buildings and sculptures to dissolve, as well as change the pH level of water sources and soil which can be detrimental to local ecosystems [4].

It is important to monitor the quality of air so that the devastating damage of air pollution can be reduced. Air quality is not the same globally, which means that air pollution monitoring systems should be placed across the world so that the main sources of air pollution can be located. Once these sources are found, solutions can be created and implemented to reduce the air pollution in the atmosphere.

The objective of this project is to design and create an air pollution monitoring system which uses free and open-source software. This means that users who have a rudimentary understanding of embedded systems can easily create this system and customise the electronics and software involved to create a more user specific air quality monitoring system.

5. IoT Air Pollution Monitoring Systems

5.1. IoT Based Air Pollution Monitoring System Using Arduino.

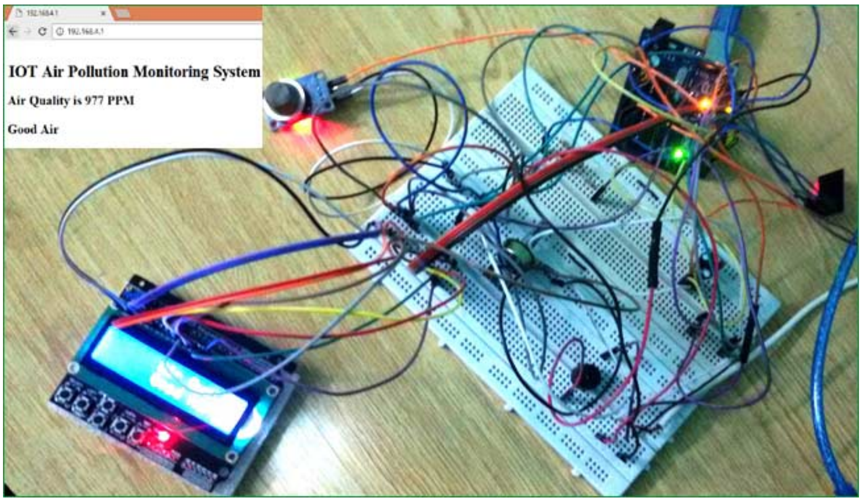

Figure 1. IoT based air pollution monitoring system using an Arduino [5].

Figure 1 shows an IoT based air pollution monitoring system (APMS) which was designed by Muhammed Aqib in December 2016 [5].

The main function of the IoT based APMS is to monitor the quality of air in the surrounding area over a web server via an internet connection. When the quality of air goes above a certain threshold value an alarm will be triggered to warn the user that there are harmful gases present in the air, such as CO_2, smoke, alcohol, benzene, and NH_3. The air quality will be displayed on an LCD screen as well as on a web page. Due to the web page, the user can access the the IoT based APMS from any location using a smartphone or a computer [5].

Aqib has provided free and open-source code as well as the circuit schematic and the components required to produce this APMS. This means that users can easily recreate the APMS and alter the design and/or the code of the APMS to match their requirements [5].

5.2. **IoT Based Air Pollution Monitoring and Forecasting System.**

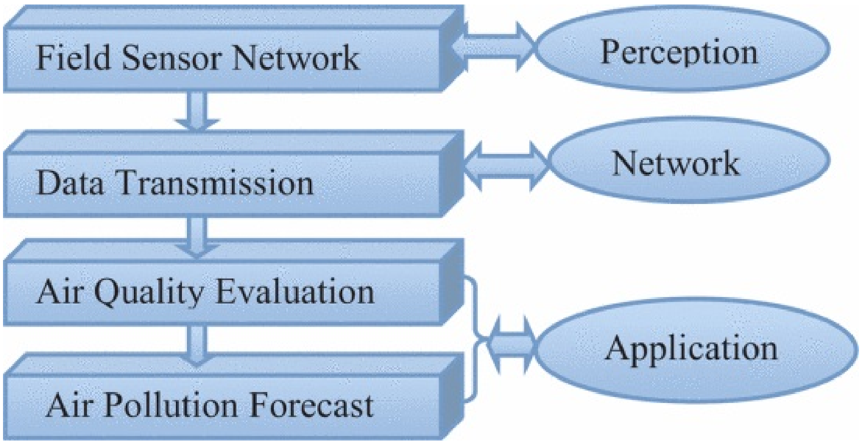

FIGURE 2. The system's integral design architecture [6].

Figure 2 shows the integral design architecture for an IoT based air pollution monitoring and forecast system (APMFS) designed by Chen, Liu, and Xu [6].

The main objective of this IoT based APMFS is to lower the production price of the average APMS through the use of IoT. The secondary objective of this APMFS is to predict the future trend of air pollution within a certain time range by analysing the data it has obtained [6].

A traditional APMS has a high precision but is also large and expensive to produce, meaning it is difficult to use for large-scale installation and not accessible to a large number of potential users. Chen, Liu, and Xu were able to reduce the price of the hardware for an APMS to one tenth of the original average price through the implementation of IoT. This means that multiple IoT based APMFSs can be located in an area to produce a monitoring sensor network [6].

This IoT based APFMS is mainly composed of a perception layer, network layer, and an application layer [6].

The perception layer mainly contains a field sensor network that is used to obtain the air pollution measurements, such as SO_2, NO_2, CO, Cl, HCl, HF, smog, and inhalable particles. The perception layer can also be used to monitor environmental conditions, such as wind direction, wind speed, temperature, humidity, and air pressure, to improve the accuracy of the air pollution diffusion forecast [6].

The network layer is used to connect all the sensors in a monitoring area to a central server. The data obtained by the sensors is then transmitted to the server in real time. The transmission system can be altered to match the service oriented requirements set by a user [6].

The application layer is used to process and analyse the data obtained from the sensors, which is then used to evaluate the quality of the air as well as predict the trend of air pollution over a period of time. A neural network can also be used to improve the accuracy of the air pollution prediction [6].

This APMFS successfully produces a cheaper alternative to the traditional APMS. It also has a successful forecast system which is approximately 90% accurate [6].

6. Requirements and Specification

6.1. Design Brief.

An APMS is to be designed to monitor and record temperature, humidity, pressure, and concentration of VOCs in the local atmosphere. This system should make use of free and open-source software and use cost efficient electronic components. This means the system should be constructed to allow anyone with a fundamental understanding of electronics and programming to easily recreate the system and make modifications to fit their own requirements.

6.2. Human and Technical Aspects.

6.2.1. *Human Aspects.*

Price of the Air Pollution Monitoring System
The price of the APMS will depend on the price of the materials used to manufacture the system, the assembly time of the system, and the cost of labour. The assembly time and cost of labour depend on whether the system is constructed by a person, machine, or a combination of both. The price will also depend on the total quantity produced in one batch. This is because the unit price of materials will reduce when buying them in bulk, hence causing a decrease in the cost of manufacturing.

From searching for other IoT based APMSs, the general price range is between £50 to £200. If this APMS is above the high threshold of £200 then the consumers may believe that the APMS is being sold for an extortionately large profit. On the other hand, if the APMS is below the low threshold of £50, then there is a risk of the materials being used in production to be of low quality. This could result in a short lifespan of the system.

Assembly Time for the Air Pollution Monitoring System
The time taken to manufacture the APMS will depend on whether the system is constructed by a person, an automated machine, or a combination of both. The time it takes for a person to construct an APMS will vary due to the competence of the worker, whereas an automated machine will produce consistent assembly times. An automated machine will have a shorter construction time when compared to the construction time of a person. Therefore, an automated machine should be used when a large number of APMSs are required.

Legal Requirements
The materials used in the construction of the APMS should be made from non-toxic and non-radioactive materials for the safety of consumers, workers, and the environment. The construction of the APMS should be carried out in a safe manner to prevent injury. The electrical connections should be designed in a way that reduces the chances of the APMS from malfunctioning.

Human Interface
The APMS should have a simple user interface that requires very intuitive inputs from the user for the system to operate as intended. The interface should be designed to cause minimal risk to the user, for example it should not shock the user and should have no sharp edges. The output of the APMS should be in an easily readable format.

6.2.2. *Technical Aspects.*

Basic Function of the Air Pollution Monitoring System
The basic function of the APMS is to monitor and record the temperature, humidity, pressure, and VOCs concentrations in the local atmosphere. The data measured by the APMS should be stored in database which can then be accessed to plot graphs, generate statistics, and export the data as a CSV file.

6.3. System Requirements.

Target of the Air Pollution Monitoring System
The APMS will be designed to use free open-source software so that anyone with basic skills in computer programming and electronics will be able to create the system and modify it to fit their own requirements. Therefore, the components used in the system should be easily accessible for anyone, meaning that they should be available at low prices from reputable online stores.

Size of the Air Pollution Monitoring System
The size of the APMS should be large enough so that it can be easily used by the visually impaired and it will not be a choking hazard for small children. The APMS should be small enough so that it can be carried by the user with only one hand, hence making the sensor portable.

What Will the Air Pollution Monitoring System Monitor?
The APMS will be required to monitor temperature, humidity, pressure, and concentration of VOCs in the local atmosphere.

Case of the Air Pollution Monitoring System
The case of the APMS should be larger than the APMS such that the system can completely fit inside it. The case should contain multiple holes to allow the air to freely flow through the casing and be accurately monitored by the APMS. The case should also provide protection against environmental hazards to the system such as precipitation and strong winds.

6.4. Design Specification.

The APMS should fit all of the following requirements:

- The cost should be between £50 and £150.
- The APMS should be durable so that it can remain in use for over a year without fault.
- The power supply should be of a standard, easily accessible type measuring 5 volts.
- There should be an input to monitor temperature.
- There should be an input to monitor humidity.
- There should be an input to monitor pressure.
- There should be an input to monitor concentration of VOCs.
- The user should be able to interact with the information obtained from the APMS via a joystick.
- There should be a visual output to display the network status and current readings of the machine.
- The visual output should be bright, clear, and easy to read.
- There should be a connection which will allow data from the APMS to be externally saved.
- The data recorded by the APMS should be stored in an SQL database with a corresponding unix timestamp.
- There should be a desktop application for the user to interact with the data recorded by the APMS.
- The desktop application should be intuitive and easy to use.
- There should be a custom PCB designed to fit all the components on.
- The PCB should be no larger than 80 mm x 60 mm.
- There should be an enclosure for the APMS to protect the APMS from environmental conditions for outdoor use.
- The enclosure should be spacious enough to comfortably house the whole APMS.
- The inputs and outputs of the APMS should be easily accessible to the user.

7. Circuit Design

7.1. Input Ideas for the Air Pollution Monitoring System.

7.1.1. *Push-to-make (PTM) Switch.*

Advantages and disadvantages:

+ PTM switches are manufactured in a variety of shapes and sizes.
+ PTM switches have a simple and intuitive user interface.
+ Current can only flow through the switch when the button is pressed.
− PTM switches lose their elasticity if the switch is used too frequently.
− The switch could break if too much force is applied.
− When the switch is pressed or released, contact bounce can occur, i.e. the metal contacts in the switch hit against each other multiple times.

A number of PTM switches could be used to interact with the APMS. Each switch could be used to move a cursor in a certain direction, for example one switch for each of an upwards movement, a downwards movement, a confirm option, and a cancel option.

7.1.2. *Joystick.*

Advantages and disadvantages:

+ Joysticks are manufactured in a variety of shapes and sizes.
+ Joysticks have a simple and intuitive user interface.
+ Joysticks can move in multiple directions, hence they can receive multiple types of input.
+ Joysticks have fast response times.
− The joystick could break if too much force is applied.
− Joystick drift could occur which means the processor could detect movement from the joystick when no movement occurs.

A joystick could be used to interact with the APMS. The joystick can move in any direction so it can be pushed upwards for an upwards movement, downwards for a downwards movement, right for a confirm option, and left for a cancel option.

7.1.3. *Thermistor.*

Advantages and disadvantages:

+ Thermistors are manufactured in a variety of shapes, sizes, and tolerances.
+ Thermistors are generally small in size which means that they can fit into small spaces.
+ Thermistors have a fast response time.
+ Thermistors are generally cheap in price.
− Thermistors have a limited temperature sensor range.
− Thermistors are prone to self-heating which can introduce errors into the recorded temperatures.
− Thermistors are non-linear.

A thermistor could be used to monitor the temperature in the surrounding area of the APMS.

7.1.4. *Figaro Air Contaminants Air Quality Sensor.*

Advantages and disadvantages [7]:

+ The Figaro sensor has a high sensitivity to gases such as hydrogen, ethanol, and carbon monoxide.
+ The Figaro sensor has a low power consumption feature, therefore the sensor will have a long operating life.
− The Figaro sensor must be calibrated before it is used.
− The operating conditions required by the Figaro sensor relies upon what the sensor will be used for.

A Figaro sensor could be used to monitor the concentration of pollutant gases in the air for the APMS.

7.1.5. ***Adafruit BME680***.

Advantages and disadvantages [8]:

+ The BME680 contains a temperature, humidity, barometric pressure, and VOC gas sensor, i.e. it can detect gasses and alcohols such as Ethanol, Alcohol, and Carbon Monoxide.
+ Either SPI or I2C wiring can be used.
+ The BME680 can measure humidity with ±3 % accuracy, barometric pressure with ±1 hPa accuracy, and temperature with ±1.0 °C accuracy.
− The BME680 needs to be operated for 48 hours when it is first used.
− The BME680 must be operated for 30 minutes in the desired mode every time it is used.
− The BME680 cannot differentiate between VOC gasses and alcohols, but can only give an overall VOC value.
− The BME680 gives a resistance value measured which depends on the VOC concentration rather than the VOC concentration itself.

A BME680 could be used to monitor temperature, humidity, pressure, and concentration of VOCs for the APMS.

7.2. **Output Ideas for the Air Pollution Monitoring System.**

7.2.1. ***Adafruit Monochrome 0.91" 128x32 I2C OLED Display***.

Advantages and disadvantages [9]:

+ The OLED has a simple and intuitive user interface.
+ The OLED has a high contrast which makes it easy to read.
+ Each pixel of the OLED can be controlled with software.
+ The OLED does not require a backlight because it can produce its own light.
− The OLED has a small screen size of 7 mm x 25 mm.
− The power required to operate the OLED depends on how many pixels are turned on.

An OLED could be used as the output for the APMS. Information could be displayed on it including the network connection status and current measurements from the sensors.

7.2.2. ***Nokia LCD 5110***.

Advantages and disadvantages [10]:

+ The LCD has a simple and intuitive user interface.
+ The LCD has low power consumption.
− The power required to operate the LCD depends on how many pixels are turned on.
− The LCD has a low resolution of 84 x 48.
− The screen may have small blemishes on it.

A Nokia could be used as the output for the APMS. Information could be displayed on it including the network connection status and current measurements from the sensors.

7.2.3. ***RJ45 8-pin Connector***.

Advantages and disadvantages [11]:

+ Wired Ethernet connections are faster at transferring data than Wi-Fi connections.
+ An Ethernet cable connection is reliable.
+ This connection will provide some security for the data being transferred because physical access to the RJ45 and the cable is required.
− The RJ45 requires a special type of cable.
− Each RJ45 can only be connected to one device; if more connections are required, then additional RJ45s are required.
− The length of the Ethernet cable limits the possible locations to place the APMS.

A RJ45 and corresponding Ethernet cable could be used to transfer the readings from the sensors to a server. The data could then be stored in a corresponding database.

7.3. Processor Ideas for the Air Pollution Monitoring System.

7.3.1. *Mbed NXP LPC1768.*

Advantages and disadvantages [12]:

+ The Mbed has two different power supply connections, i.e. VIN and a mini USB port.
+ The Mbed can provide two different output voltages, i.e. 3.3 V or 5 V.
+ The Mbed pin separation matches the standard breadboard hole separation, hence allowing for testing on a breadboard.
+ Multithreading is very easy to incorporate in the code.
+ The Mbed is very power efficient.
− The online Mbed compiler has poor debug help and no automatic code formatting or highlighting.
− Has a smaller range of open-source libraries to use compared to other microcontrollers.
− Only uses C and C++ programming languages.

A Mbed could be used as the processor for the APMS.

7.3.2. *Espressif ESP32-WROOM-32U.*

Advantages and disadvantages [13]:

+ The ESP32 provides two different output voltages, i.e. 3.3 V or 5 V.
+ The ESP32 pin separation matches the standard breadboard hole separation, hence allowing for testing on a breadboard.
+ The ESP32 has a Wi-Fi and Bluetooth module.
+ C, C++, and Arduino C are all supported programming languages.
+ Has a large range of open-source libraries because of a large community.
− The ESP32 is larger in size than other microprocessors.
− May suffer from feature creep when used for an APMS.

An ESP32 could be used as the processor for the APMS.

7.4. Power Supply Ideas for the Air Pollution Monitoring System.

7.4.1. *DC Power Jack.*

Advantages and disadvantages:

+ DC power jacks are manufactured in a variety of shapes and sizes.
+ DC power jacks allow DC power supplies with different voltages to be connected if the appropriate connector is available.
− DC power jacks are designed to only accept one size of connector.
− The design of DC power jacks is not standardised.
− The DC power jack can become damaged over time due to frequent connections and disconnections.

A DC power jack could be used to connect a DC power supply to the APMS.

7.4.2. *Cable for the Microprocessor.*

Advantages and disadvantages:

+ The cable can be connected directly to the microprocessor.
− The length of the cable limits the possible locations to place the APMS.

A cable can be directly connected to the microprocessor to provide power. The microprocessor can then be used to power the other components for the APMS.

7.5. **Prototype Ideas for the Air Pollution Monitoring System.**

7.5.1. ***Prototype Idea 1.***

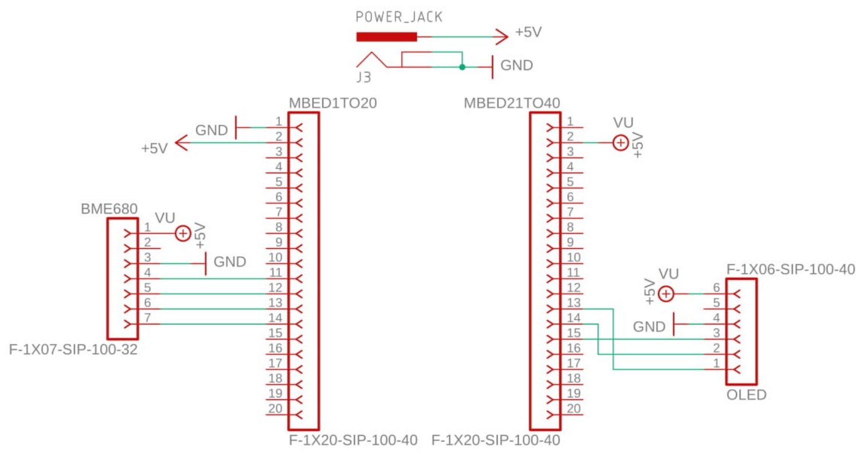

FIGURE 3. Schematic of Prototype 1.

The prototype shown in Figure 3 will display the current measurements of temperature, humidity, perssure, and VOC concentration obtained from the BME680 on the OLED. The prototype contains a DC Power Jack, BME680, Mbed and OLED. The pins of the BME680, Mbed, and OLED are represented by female headers. For the MBED21TO40 female header, pin 20 of the female header is p21 of the Mbed and pin 1 of the female header is the VOUT pin of the Mbed.

The DC Power Jack has three pins which are as follows [14]:

- Tip: Provides a DC voltage when a DC voltage source is connected.
- Plug Detection: Detects if a plug has been connected.
- Sleeve: Requires a connection to ground.

A 5 V DC power supply is connected to the DC power jack. The Tip pin is connected to the VIN pin of the Mbed to supply the microprocessor with power. The Plug Detection and Sleeve pins are connected to the GND pin of the Mbed. The Plug Detection pin is connected to ground because the APMS will not monitor if a plug has been connected to the DC Power Jack [12].

The BME680 has seven pins which are as follows [15]:

- VIN: Requires a connection to a 3 V to 5 V supply.
- 3Vo: Provides a 3.3 V regulated output.
- GND: Requires a connection to ground.
- SCK: The SPI Clock pin, which is an input for the BME680.
- SDO: The is the Serial Data Out pin, which sends data from the BME680 to the Mbed.
- SDI: The Serial Data In pin, which receives data from the Mbed to the BME680.
- CS: The Chip Select pin, which is used to start an SPI transaction.

The VIN pin is connected to the VU pin of the Mbed becuase it provides a 5 V supply. Also, the GND pin of the BME680 is connected to the GND pin of the Mbed. This prototype design uses SPI wiring to connect the BME680 to the Mbed, hence Mbed pins p11, p12, p13, and p14 are connected to pins SCK, SDO, SDI, and CS of the BME680 [12].

The OLED has six pins which are as follows [16]:

- VIN: Requires a connection to a 3 V to 5 V supply.
- 3Vo: Provides a 3.3 V regulated output.
- GND: Requires a connection to ground.
- Reset: Resets the OLED.
- SCL: Requires a connection to an I2C SCL.
- SDA: Requires a connection to an I2C SDA.

The VIN pin is connected to the VU pin of the Mbed becuase it provides a 5 V supply. Also, the GND pin of the OLED is connected to the GND pin of the Mbed. The Reset pin is a digital input so it connects to p26 of the Mbed. The SCL pin is connected to p27 of the Mbed because p27 is an I2C SCL pin. The SDA pin is connected to p28 of the Mbed because p28 is an I2C SDA pin [12].

7.5.2. ***Prototype Idea 2.***

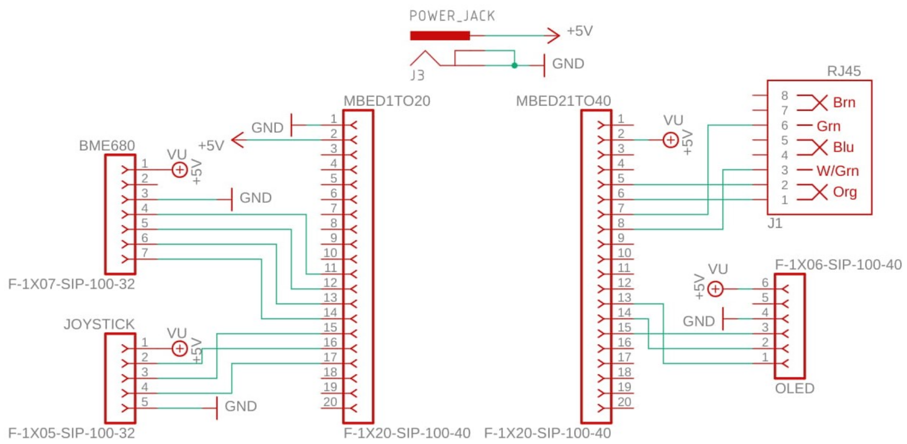

FIGURE 4. Schematic of Prototype 2.

The prototype shown in Figure 4 will record measurements temperature, humidity, perssure, and VOC concentration once every minute. The measurements will be sent from the Mbed to a server using the RJ45 and the appropriate cable. The measurements will be stored in a database written in SQL and can then be exported as a CSV file. The joystick will be used to navigate the menu displayed on the OLED, which will show either the network status or current readings.

The prototype contains a DC Power Jack, BME680, Joystick, Mbed, OLED and RJ45. The pins of the BME680, Joystick, Mbed, and OLED are represented by female headers. For the MBED21TO40 female header, pin 20 of the female header is p21 of the Mbed and pin 1 of the female header is the VOUT pin of the Mbed. This prototype has the same components as Prototype Idea 1, hence these components have the same wiring as mentioned previously. However, Prototype Idea 2 also contains a joystick and a RJ45.

The joystick has five pins which are as follows [17]:
- VCC: Requires a connection to a 3 V to 5 V supply.
- VERTZ: Provides data relating to the vertical position of the joystick.
- HORZ: Provides data relating to the horizontal position of the joystick.
- SEL: Provides a digital input for the joystick's push-to-make switch.
- GND: Requires a connection to ground.

The VCC pin is connected to the VU pin of the Mbed because it provides a 5 V supply. Also, the GND pin of the Joystick is connected to the GND pin of the Mbed. The SEL pin is connected to p17 of the Mbed because it provides a digital input. The VERTZ and HORZ pins are connected to P15 and p16 respectively because they provide analogue inputs [12].

The RJ45 has eight pins, but only four are required for this system, which are as follows [18]:
- Pin 1: The Rc+.
- Pin 2: The Rc-.
- Pin 3: The Tx+.
- Pin 6: The Tx-.

Pins 1, 2, 3, and 6 of the RJ45 are connected to the RC+, RC-, TX+, and TX- pins of the Mbed respectively [12].

7.6. Bill of Materials.

7.6.1. *Prototype Idea 1 Bill of Materials.*

Component Name	Product Code	Unit Cost (£)	Number of Components	Total Price (£)	Reference
DC Barrel Power Jack/Connector	COM1303	1.50	1	1.50	[19]
5W Plug Adapter 5V DC	175-3292	5.24	1	5.24	[20]
Adafruit BME680	3660	18.95	1	18.95	[8]
Mbed NXP LPC1768	703-9238	58.04	1	58.04	[21]
Adafruit Monochrome 0.91" 128x32 I2C OLED Display	4440	12.50	1	12.50	[9]

Table 1. Bill of materials for Prototype 1.

From Table 1, it can be seen that the total price for one APMS is £96.23.

7.6.2. *Prototype Idea 2 Bill of Materials.*

Component Name	Product Code	Unit Cost (£)	Number of Components	Total Price (£)	Reference
DC Barrel Power Jack/Connector	COM1303	1.50	1	1.50	[19]
5W Plug Adapter 5V DC	175-3292	5.24	1	5.24	[20]
Adafruit BME680	3660	18.95	1	18.95	[8]
Thumb Joystick	COM-09032	3.00	1	3.00	[17]
Breakout Board for Thumb Joystick	BOB-09110	1.80	1	1.80	[22]
Mbed NXP LPC1768	703-9238	58.04	1	58.04	[21]
Adafruit Monochrome 0.91" 128x32 I2C OLED Display	4440	12.50	1	12.50	[9]
RJ45 8-Pin Connector	PRT-00643	1.50	1	1.50	[23]
SparkFun RJ45 Breakout	BOB-00716	0.95	1	0.95	[24]
RJ45 CAT6 Cable 5 m	411-328	6.64	1	6.64	[25]

Table 2. Bill of materials for Prototype 2.

From Table 2, it can be seen that the total price for one APMS is £110.12.

8. Test Techniques and Results For the Prototypes

8.1. Prototype Idea 1.

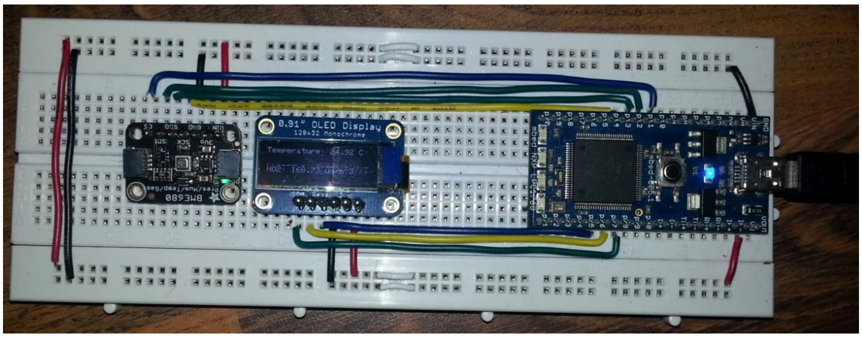

Figure 5. Prototype Idea 1 on a breadboard.

From Figure 5, it can be seen that the circuit design for Prototype Idea 1 has been assembled on a breadboard. This breadboard circuit will be used to test both the performance and the validity of the results of the prototype. The breadboard circuit will also be used to produce user tests that will allow a user to test the functionality of the prototype.

8.1.1. *Prototype Idea 1 Quality Testing*.

The breadboard circuit shown in Figure 5 was used to monitor the temperature, humidity, pressure, and VOC concentration in the local atmosphere. The temperature, humidity, pressure, and VOC readings were tested by various methods.

To test the temperature sensor, the reading shown on the OLED display was compared to a thermometer reading three times, each separated by 15 minutes, on three different days. The temperature recorded by the sensor was always within ± 1 °C of what was shown on the thermometer. Additionally, placing a finger over the sensor caused the temperature reading to increase, which was the expected result because body temperature is higher than room temperature.

To test the humidity sensor, the sensor was breathed on. This increased the humidity reading, which was the expected result because a human breath is very moist compared to the atmospheric humidity. This process was repeated two more times, each separated by 15 minutes, on three different days, and the humidity increased as expected each time. There was no access to a hygrometer to directly compare the humidity readings with in order to test the accuracy of this sensor.

To test the pressure sensor, the reading shown on the OLED display was compared to a barometer reading three times, each separated by 15 minutes, on three different days. The pressure recorded by the sensor was always within ± 1 hPa of what was shown on the barometer.

To test the VOC sensor, a reading was taken before and after a wood fire was lit on an indoor fireplace. This was done because wood fires produce several different types of VOC gasses. The VOC concentration reading increased after the fire was lit, which was the expected result. This process was repeated two more times on different days, and the VOC concentration increased as expected each time. There was no access to a commercial APMS to directly compare the VOC concentration readings with in order to test the accuracy of this sensor.

The results obtained these experiments show the sensors to be of a high quality. This is because the readings were very accurate where comparison was possible and the sensors showed the expected change in readings when they were subject to different conditions. The prototype has also performed well as the sensors where able to function as intended at any time of day.

8.2. **Prototype Idea 2.**

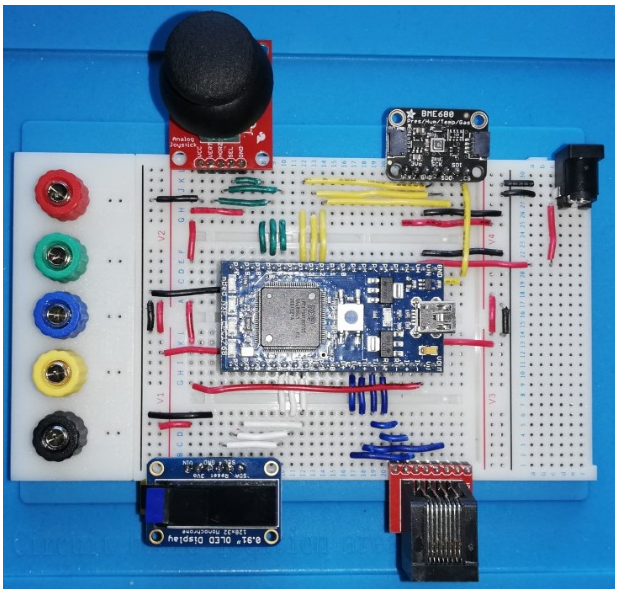

FIGURE 6. Prototype Idea 2 on a breadboard.

From Figure 6, it can be seen that the circuit design for Prototype Idea 1 has been assembled on a breadboard. This breadboard circuit will be used to test both the performance and the validity of the results of the prototype. The breadboard circuit will also be used to produce user tests that will allow a user to test the functionality of the prototype.

8.2.1. ***Prototype Idea 2 Quality Testing.***

The breadboard circuit shown in 6 was used to monitor and record the temperature, humidity, pressure, and VOC concentration in the local atmosphere for 24 hours. The data obtained from the 24 hour monitoring period can be seen in Figure 7 below.

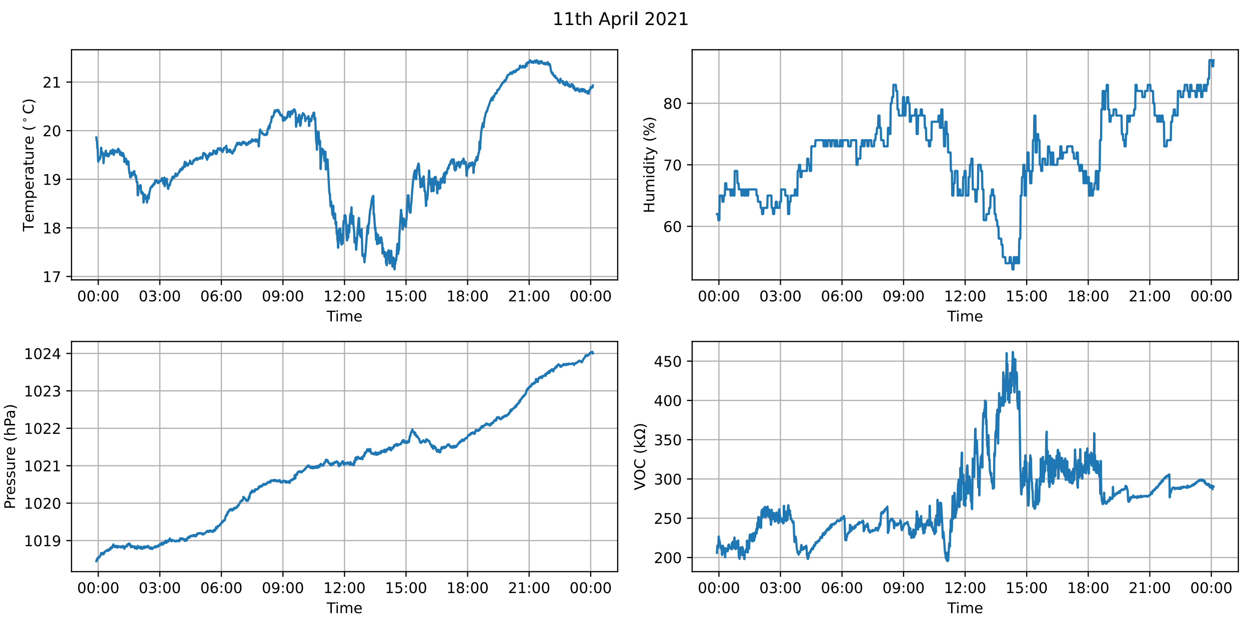

FIGURE 7. APMS data recorded by Prototype Idea 2 on the 11$^{\text{th}}$ April 2021.

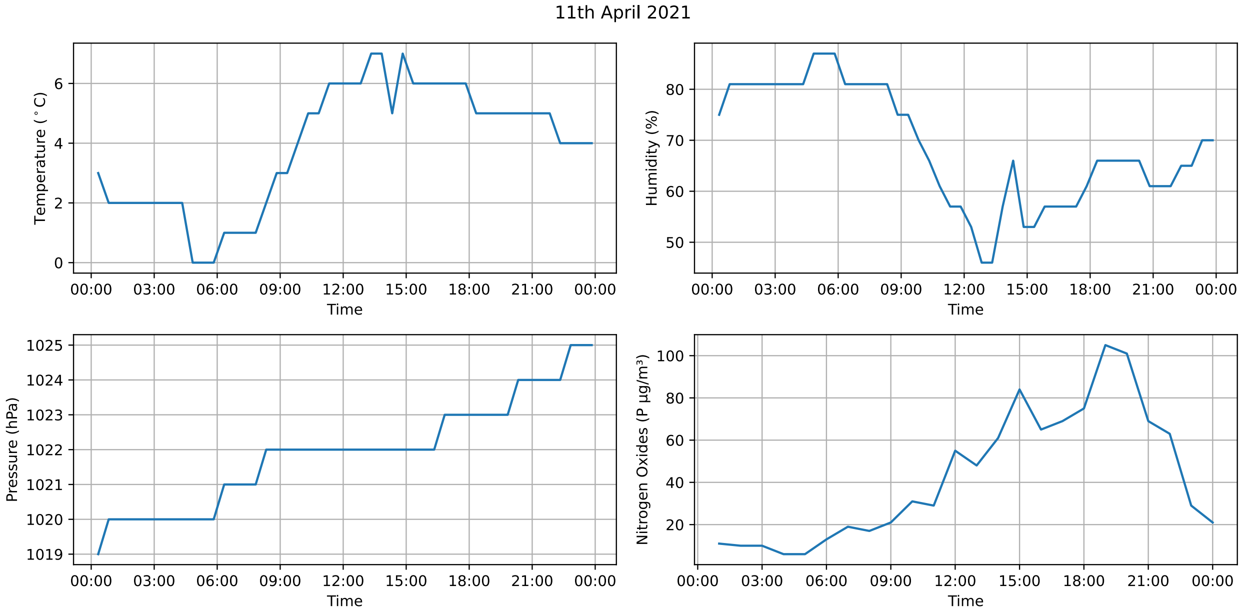

FIGURE 8. APMS data for the Larne District and Antrim Road, Newtownabbey on the 11^{th} April 2021.

Figure 8 shows data obtained from two monitoring systems. The data for the temperature, humidity, and pressure graphs have been obtained from a monitoring system at Larne District [26]. The nitrogen oxides data for the graph has been obtained from a monitoring system at Newtownabbey Antrim Road (NAR) [27]. This is because the Larne District APMS does not gather pollutant data and Newtownabbey is the nearest settlement of similar size geographically with recorded VOC data. Unfortunately, the only VOC which is recorded at the NAR APMS is nitrogen oxides, but this is the most common VOC in the local atmosphere. The prototype used for gathering data was roughly located 1 mile from the Larne District APMS and 14 miles from the NAR APMS.

From Figures 7 and 8, it can be seen that the prototype graphs fluctuate more than the Larne District and NAR graphs. The reason why the prototype graphs fluctuate more could be due to the prototype sampling more results in the 24 hour time frame, as it records a result every minute instead of every half hour. Also, the BME680 is likely to be less accurate than the sensors used by the Larne District and NAR monitoring systems. Another reason is that the prototype had slightly different environmental conditions than the Larne District and NAR APMSs due to the slightly different geographical locations. The main reason, however, can be attributed to the location of the prototype being inside a house whereas the Larne District and NAR APMSs are located outside. The prototype was located inside because it did not have a physical enclosure to protect it from environmental conditions, although such an enclosure has been designed digitally.

From Figures 7 and 8, it can be seen that the prototype temperature graph is not similar to the Larne District temperature graph. They do not follow the same trend because the prototype was measuring the temperature inside a house instead of outside. From Figure 7, it can also be seen that the temperature rapidly decreased to 17.5 °C between 12:00 to 15:00. This is because it was more windy outside the window hence more cold air entered the house where the sensor was located.

From Figures 7 and 8, it can be seen that the prototype humidity graph is similar to the Larne District humidity graph. They roughly follow the same trend and they have similar values.

From Figures 7 and 8, it can be seen that the prototype pressure graph is nearly identical to the Larne District pressure graph. They follow the same trend and they have very similar values.

From Figures 7 and 8, it can be seen that the prototype VOC graph is similar to the NAR nitrogen oxides graph. Although the different units mean the graphs cannot be directly compared, it can be observed that they follow the same trends for the data. The most notable difference in these graphs is that the prototype measured a more exaggerated peak from approximately 13:00 to 15:00. This is because the prototype was located in close proximity to three local churches and the results were recorded on a Sunday, hence there was a peak in traffic at this time.

The results obtained from the prototype are therefore shown to be of a high quality because they followed the same trends and had similar values to officially recorded data for three of the four graphs. The exception of the temperature can be attributed to the fact that the prototype was used indoors and the Larne District measurements were taken outdoors. The prototype has also performed well as it was able to send the results from the BME680 to a database on a computer for the full 24 hours without any errors or lost data.

8.3. **Operational User Tests.**

Test Type	Test Data	Expected Result	Actual Result	Prototypes Tested
1) Change the selected submenu on the OLED GUI home screen	Press down on the joystick	Scrolls to a different option	Worked as intended	Prototype Idea 2
2) View a submenu on the OLED GUI	Press right on the joystick	Transitions to the Network Status submenu	Worked as intended	Prototype Idea 2
3) Return to the home screen on the OLED GUI	Press left on the joystick	Transitions to the home screen	Worked as intended	Prototype Idea 2
4) Test the temperature sensor	Cover the sensor with a finger	Increases value of the reading	Worked as intended	Both prototypes
5) Test the humidity sensor	Breath on the sensor	Increases value of the reading	Worked as intended	Both prototypes
6) Test the VOC gas sensor	Light a wood fire	Increases value of the reading	Worked as intended	Both prototypes
7) Test the temperature sensor	Compare the reading with a thermometer	Reading accurate within $\pm$ 1 °C	Worked as intended	Both prototypes
8) Test the pressure sensor	Compare the reading with a barometer	Reading accurate within $\pm$ 1 hPa	Worked as intended	Both prototypes
9) Test custom date and time ranges for graph plotting	Enter two specific date and times	Graphs update to only show data in this time range	Worked as intended	Prototype Idea 2
10) Export data as a CSV file	Click the “Export” button	Creates a CSV file	Worked as intended	Prototype Idea 2

TABLE 3. Operational user tests for both prototypes.

8.4. **Evaluation of Performance.**

Both prototypes have been shown to function as intended by the quality and user tests, hence they are both successful prototypes. However, the performance of Prototype Idea 2 is the best of the two prototypes. This is because it offers the more exclusive features, such as having a more in depth OLED GUI, storing the results in a database, and having an associated desktop application. It was also tested for a longer time period and experienced no errors. Unfortunately, the PCB and enclosure were only designed digitally and not manufactured, hence testing could not occur for these items.

9. OLED GUI

9.1. **Home Screen.**

FIGURE 9. The Home Screen of the OLED GUI.

Figure 9 shows the home screen of the OLED GUI. There are two options of "Network Status" and "Current Readings", which can be selected by scrolling up or down with the joystick. The option which is currently selected is shown on the display with a ">" character. Scrolling right with the joystick will transition the display to the respective submenu. This screen is only present in Prototype Idea 2.

9.2. **Network Status.**

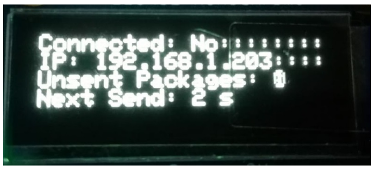

FIGURE 10. The Network Status submenu of the OLED GUI.

Figure 10 shows the Network Status submenu of the OLED GUI. Scrolling left with the joystick will transition the display back to the Home Screen. The data updates on the display every half a second. This screen is only present in Prototype Idea 2.

This submenu includes four pieces of information, which are:
- Connected: Whether the APMS is successfully connected through ethernet.
- IP: The IP address which the APMS is connected to.
- Unsent Packages: The number of unsent packages of data sent to the server.
- Next Send: The time until the next attempt to send data to the server, in seconds.

9.3. **Current Readings.**

FIGURE 11. The Current Readings submenu of the OLED GUI.

Figure 11 shows the Current Readings submenu of the OLED GUI. Scrolling left with the joystick will transition the display back to the Home Screen. The data updates on the display every half a second. This screen is present in Prototype Idea 1 and Prototype Idea 2.

This submenu includes four pieces of information, which are:
- Temperature: The temperature in degrees Celsius, to two decimal places.
- Humidity: The humidity as a percentage, to the nearest integer.
- Pressure: The pressure in hectopascals, to two decimal places.
- VOC: The resistance correlating to the concentration of VOCs in kiloohms, to two decimal places.

10. Desktop Application

10.1. Main Menu.

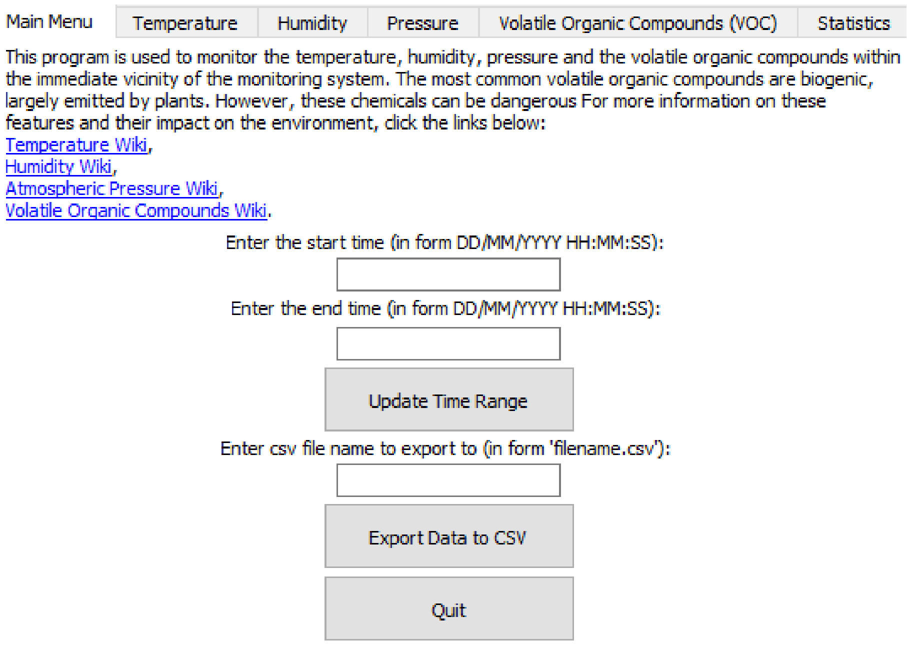

Figure 12. The main menu of the desktop application.

Figure 12 shows the main menu of the desktop application. There is a brief overview of the APMS at the top of this screen with hyperlinks relating to each of the four readings. There are two text boxes to enter the start and end times of the data which is to be analysed graphically and statistically. Clicking the "Update Time Range" button will submit these start and end times. There is also a text box to enter a file path to export the data as a CSV file. Clicking the "Export Data to CSV" button will export the data in the time range which has been most recently entered to a CSV file. The last feature on this screen is a "Quit" button which will close the desktop application when clicked.

10.2. Graphs Tabs.

Figure 13 on the next page shows the temperature graph tab of the desktop application. This tab shows a graph of the readings for temperature in a given time range. There are similar tabs for humidity, pressure, and VOCs.

10.3. Statistics Tab.

Figure 14 on the next page shows the statistics tab of the desktop application. This tab shows a statistical analysis of each of the four readings in a given time range. The statistics shown are:

- Mean
- Median
- Mode
- Range
- Inter-quartile range
- Standard deviation
- Variance
- Maximum value of the reading
- Time at which the maximum reading occurs
- Minimum value of the reading
- Time at which the minimum reading occurs

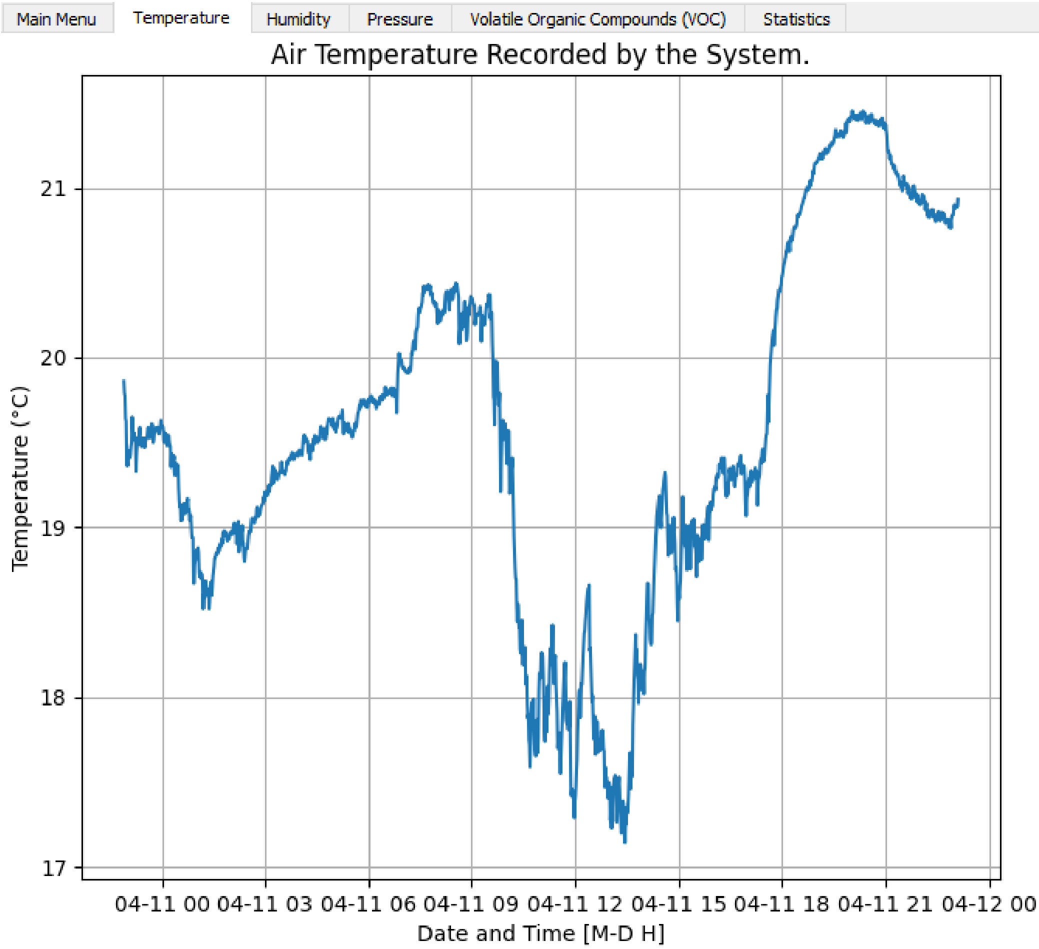

FIGURE 13. The temperature graph created on the desktop application.

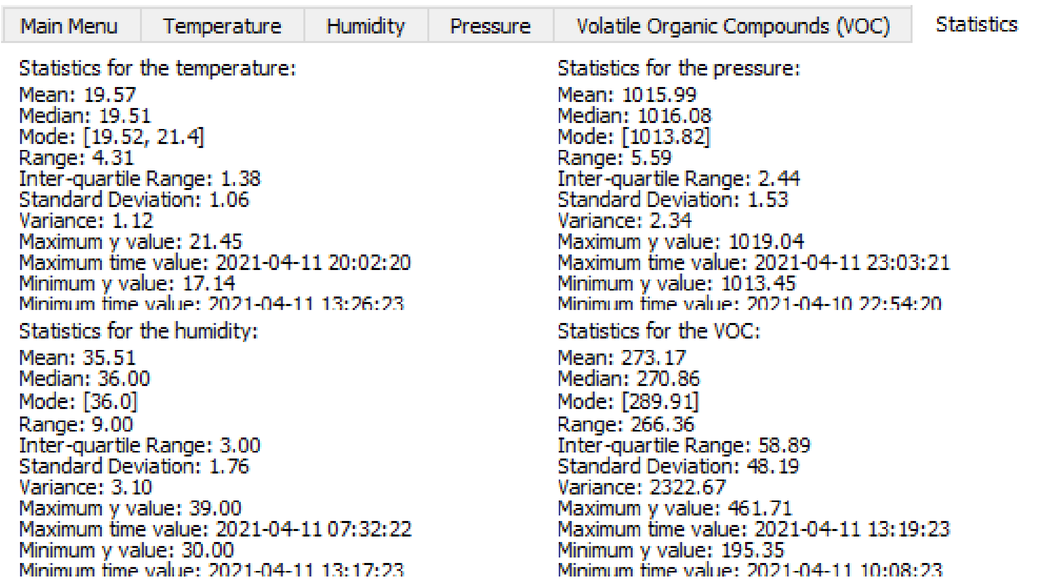

FIGURE 14. The statistics tab on the desktop application.

11. PCB

11.1. **Through-hole or Surface Mounted?**

Through-hole mounted components involve inserting the component's legs into holes which are drilled into the PCB. The component's legs are then soldered and cut to an appropriate size, which provides an electrical connection as well as mechanical support. On the other hand, surface mounted components involve placing the components onto the surface of the PCB. The component's legs are then soldered which provides an electrical connection.

Through-hole mounted components are able to withstand more mechanical stress than surface mounted components and are easier to solder for users with little soldering experience. However, through-hole mounted components require holes to be drilled into the PCB which is expensive and time consuming, whereas surface mounted components do not require these holes. Also, the drill holes also limit the area available for the PCB traces because the drill holes go through all the layers of the PCB. Surface mounted components are generally smaller than their through-hole mounted counterparts, which allows the overall size of the PCB to decrease.

For the APMS, all the components will be through-hole mounted because they will be more durable than their surface mounted components. Additionally, the easier soldering process will benefit users with a limited soldering experience.

11.2. **Solder Mask and Silkscreen.**

The solder mask layer will prevent the solder bridging between adjacent traces. Also, the solder mask layer can help reduce the effect of corrosion on the exposed traces. The silkscreen layer will reduce the likelihood of components being soldered into incorrect positions by providing text or an image, labelling where the components should be placed.

The addition of the solder mask and silkscreen layers will increase the cost to manufacture the PCB, but decrease the chances of errors occurring during production. Therefore, the PCB will have a solder mask and a silkscreen layer.

11.3. **Single-sided or Double-sided?**

A single-sided PCB will only have traces on one side of the PCB which means that the components can only be mounted onto one side. On the other hand, a double-sided PCB will have traces on both sides of the PCB which means that the components can be mounted onto both sides.

The main advantage of a double-sided PCB compared to a single-sided PCB is that there is a larger area to place traces which enables more complex routing. This will reduce the size of the PCB which will reduce the production cost for the PCB. However, a single-sided PCB will be quicker to manufacture than a double-sided PCB because the single-sided PCB will have a less complex design.

The PCB used in the APMS will be double-sided because it will be smaller in size than a single-sided PCB.

11.4. **Aesthetic Layout.**

The PCB of the APMS will be designed for Prototype Idea 2 instead of Prototype Idea 1. This is because Prototype Idea 2 allows measurements for temperature, humidity, pressure, and VOC concentration to be viewed live and stored in a database. This data can then be plotted on graphs, analysed, and exported as a CSV file.

One side of the PCB should be used for the user interface only, whereas the other side should contain all the other components to avoid cluttering the user interface. The DC Power Jack and the RJ45 should be placed at the edge of the PCB to allow the cables to be easily connected and disconnected so that they do not have to cross over other components on the PCB. All components should be in close proximity to each other to reduce the size of the PCB.

11.5. **PCB Design.**

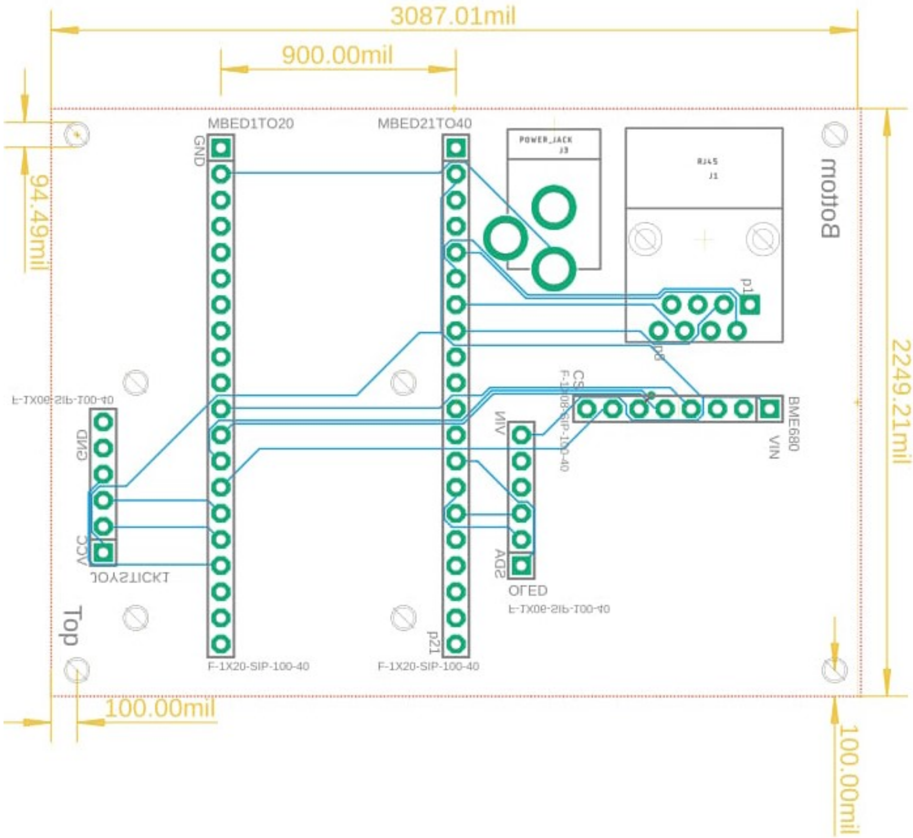

FIGURE 15. PCB Design showing the connections of the components.

From Figure 15, it can be seen that:

- The PCB dimensions are 3087.01 mil x 2249.21 mil (78.4 mm x 57.1 mm), which matches the design specification of being smaller than 80 mm x 60 mm.
- The "MBED1TO20" and "MBED21TO40" are 900 mil away from each other to match the spacing of the Mbed pins.
- There are drill holes in the corners of the PCB which will be used to attach support beams between the PCB and the enclosure. These drill holes are 94.49 mil in size so that M2 screws can be inserted them [28].
- The DC Power Jack and the RJ45 have been placed at the edge of the PCB to the cables to be easily connected and disconnected without crossing over any components.
- The OLED and the joystick have been placed at the bottom of the PCB while the other components have been placed at the top of the PCB. This simplifies the user interface.
- The silkscreen layer has been used to label the pin connections, the components, the top and bottom sides of the PCB, the outline of RJ45, and the DC Power Jack. This will reduce the likelihood of components being soldered into the wrong position.

The PCB shown in Figure 15 does not include the GND plane which is present in the real PCB. This is because including the GND plane in Figure 15 makes it too hard to distinguish the traces and read the silkscreen layer. The GND plane is present in the real PCB because it simplifies the layout of the PCB traces, i.e. it provides access to the ground net anywhere that a via can be used.

12. Enclosure

12.1. Requirements for the Enclosure's Usability.

The enclosure should have good air ventilation so that the results obtained by the BME680 are not affected by the casing, i.e. the readings inside of the enclosure should equal the readings outside of the enclosure. This can be achieved by having several openings which allow air to flow through the enclosure.

The enclosure should be able to be placed on a flat surface or hung on a wall. This can be achieved by designing the enclosure to have a flat bottom, as well as having holes at the back to allow screws or hooks to be used for hanging it on a wall.

The enclosure should be able to be located inside or outside. This means the enclosure should protect the PCB from environmental conditions, such as precipitation, ultraviolet light, and wind. This could also increase the lifespan of the APMS by physically protecting the components from external damage. This can be achieved by completely encasing the PCB with the exception of small holes on the sides of the enclosure to allow air flow throughout the enclosure.

12.2. Requirements for the Enclosure to Contain the PCB.

The enclosure should be larger than the PCB so that the enclosure can fully encase the PCB.

There should be easy access to the RJ45 and the DC Power Jack so that the cables can be connected and disconnected when the PCB is inside the enclosure. The enclosure should have a gap that the two cables could fit through.

The enclosure should be able to securely hold the PCB in place. This can be achieved by using four support beams on the inside of the enclosure which would connect the PCB to the enclosure via four M2 screws.

The user should be able to mount the PCB inside the enclosure. This can be achieved by designing the underside of the enclosure so that it can be disassembled, enabling easy mounting of the PCB inside the enclosure.

The user should be able to interact with the joystick when the PCB is inside the enclosure. This can be achieved by having a gap for the joystick to fit through.

The user should be able to view the OLED display when the PCB is inside the enclosure. This can be achieved by using a see through material, such as glass, to have a small window for viewing.

12.3. Aesthetic Layout.

The enclosure should have a light colour scheme so that it can be easy to locate when it is placed outside. The light colour scheme will also reduce the amount of heat absorbed from light sources, which will protect the PCB from damage caused by direct exposure to sunlight for long periods of time.

The enclosure should have a distinct marking that distinguishes Team 6 as the creators of the APMS.

The edges of the enclosure should be rounded so that the user is unable to cut themselves on the enclosure.

12.4. **Enclosure Design.**

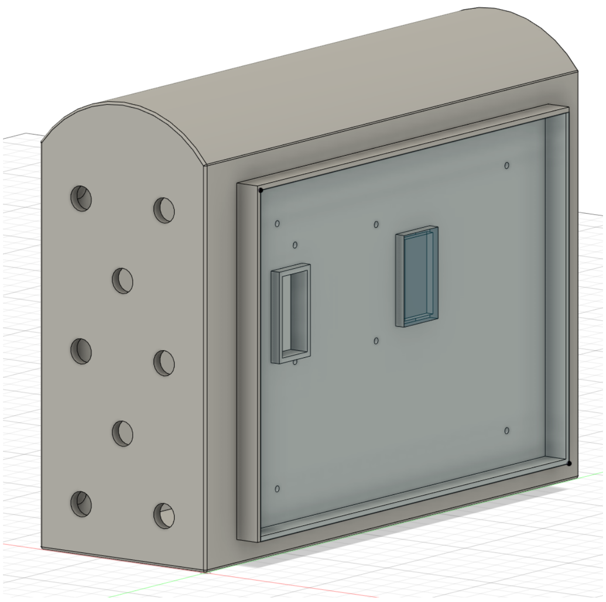

Figure 16. Front view of the enclosure.

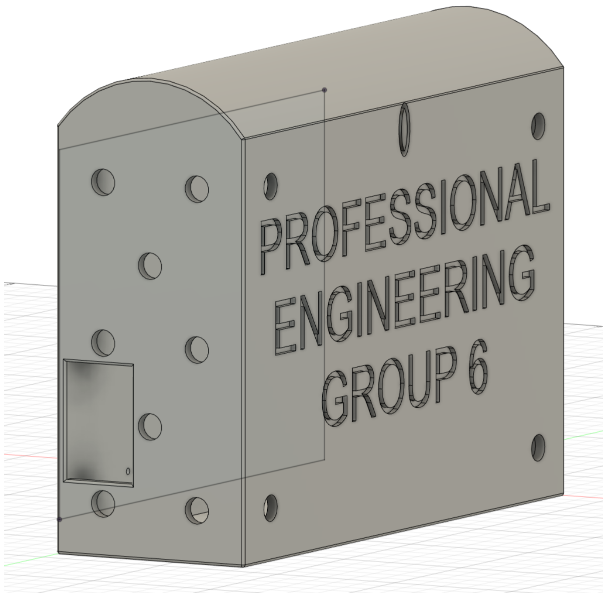

Figure 17. Back view of the enclosure.

From Figure 16, it can be seen that:

- The dimensions of the main body of the enclosure are 39.5 mm x 119.5 mm x 79.83 mm, which is larger than the PCB (78.4 mm x 57.1 mm).
- The height of the round shell at the top of the enclosure is 9.67 mm.
- The front panel with the screen is larger than the PCB, allowing it to fit in the screen.
- There are two small rectangular shapes on the front panel of the enclosure. The rectangular gap with the see through glass screen is where the OLED display will be located. The rectangular gap without the see through glass screen is where the joystick will be located.
- There are eight small holes on the front panel of the enclosure. These are used to secure the PCB and joystick to the enclosure via eight M2 screws.
- One side panel of the enclosure has eight holes, each with a radius of 2.5 mm, which allows air to flow through the enclosure.
- The top panel of the enclosure is curved to allow raindrops to flow down the front and back panels of the enclosure. This reduces the amount of water which will get stuck on top of the enclosure or enter through the small holes on the sides of the enclosure.

From Figure 17, it can be seen that:

- There is a small rectangular gap on the side panel, which allows users to easily connect and disconnect the cables to the PCB.
- The other side panel of the enclosure also has eight holes, each with a radius of 2.5 mm, which allows air to flow through the enclosure.
- The text "PROFESSIONAL ENGINEERING GROUP 6" has been etched into the back panel of the enclosure so that the APMS is easily identifiable.
- There are four screw holes in the four corners of the back panel of the enclosure, so that it can be screwed onto a wall. Additionally, there is an ovular hole at the top of the back panel to allow the enclosure to be hung on a wall with a hook.

The entire enclosure should be made of polypropylene (PP), a widely used type of plastic. It has high impact resistance and strong mechanical properties, so it can be used outdoors for long periods of time. It is also resistant to a variety of organic solvents as well as acid and alkali corrosion. PP has an average density of approximately 0.9 g/cm^3, so it is a low-density polymer material that creates a very lightweight enclosure [29].

13. Discussion

13.1. General Analysis.

Prototype Idea 2 meets the design requirements that were given to a high standard. The sensors have a high accuracy, the system can operate for over 24 hours at a time, and there are no known bugs in the system functionality. There are some small issues and improvements which could be made. The price of the prototype is close to the upper bound which was outlined in the design specification. The prototype also uses easily accessible components and free open-source software which means that anyone with a fundamental skill set can create and adapt the system to fit their own needs.

13.2. Issues of the System.

Artifacting on the OLED
The OLED GUI produces artifacting on the "Network Status" and "Current Readings" submenus. This occurs at the end of most lines on these submenus in the form of colons appearing in place of space characters. This makes the GUI look clustered and unprofessional.

VOC Concentration Units
The unit used for measuring the VOC concentration is in kiloohms. This is due to the sensor measuring a resistance which correlates to the VOC concentration. This means that only a trend can be observed through these readings because readings in the standard units for VOC concentration are not present.

Only One Gas Measurement
Only one gas measurement is recorded by the APMS, which is VOC concentration. The BME680 can only record this general VOC measurement and cannot record measurements for specific types of VOC gasses or other pollutant non-VOC gasses.

Two Cables Required
Both an Ethernet cable and voltage supply cable are required to be connected to the APMS. This means that the cable lengths heavily restrict the locations that the system can be placed. Additionally, these cables require a network and electricity source to connect to.

Must Reset the Mbed to Reconnect
If the Ethernet connection is lost and regained, the Mbed must be reset so that the connection to the server can be reestablished. This is an inconvenience to the user and readings taken after the disconnect occurred may be lost.

Time Zone Incompatibility
The database stores a unix timestamp for each reading. The desktop application reads these timestamps and converts them to British Summer Time, BST (GMT+1), because this was the time zone that the application was created in. This means that other time zones are not accounted for in the software, so all users will see their results converted to BST.

13.3. Improvements.

Convert VOC Concentration Units
The VOC concentration units may be converted from $k\Omega$ to the standard units of $\mu g/m^3$. This can be done by implementing a precompiled binary file available on the Bosch official website [30]. This would enable readings to be taken which can be directly analysed. These readings may also be used for comparison with readings from other APMSs.

Error Handling for Networking
The APMS will not reconnect automatically if disconnected from the server at any point. To fix this issue, more error handling can be added via the source code. This would be more convenient to the users and would ensure no recorded measurements would be lost.

Different IP types
The APMS can only use dynamic IPv4 addresses. However, it could be modified via the source code to allow for dynamic and static IP addresses to be used. Moreover, IPv6 addresses could also be implemented so that they may be used if required. This would be of a greater convenience to the users.

Use a Separate Thread or Interrupts for the Joystick
The joystick currently operates on the same thread as the sensors. This means that there is a high loop time in this thread. To reduce this, the joystick could be to its own thread or it could use an interrupt service routine instead. This could allow for readings to be taken more frequently.

Comparison of Readings with other Data
The desktop GUI currently calculates statistics for a given time range of data. However, this could be improved so that the statistics gathered from one time range could be directly compared to the statistics from a second given time range. Furthermore, functionality could be added to import data from other systems for comparison of the statistics. This would be a massive convenience to the users of the system and would create another unique selling point for the APMS.

13.4. **Cost Reduction.**

The cost of the APMS is predicted to be approximately £140 to account for the cost of components and labour while maintaining a profit. This means that the APMS is more expensive than some comparable products, even though it is cheaper than the highest allowed price of £150 in the design specification. Therefore, potential users may choose a cheaper alternative to this APMS at the expense of some features.

The first way which prices could be reduced would be to replace the Mbed microcontroller (£58.04) [21] with an ESP32 development board (£14) [31]. This could reduce the cost by over £40, but would involve porting the code to be compatible with a different microcontroller.

Another method to reduce the price would be to source the components from other vendors at cheaper prices. This method relies on finding a reliable vendor with cheaper prices, however none have been found online. If a less reputable vendor was used for lower prices, then the components received may not be as high quality or could have a shorter lifespan.

Furthermore, price could be reduced by buying the components in higher quantities for manufacturing. This would reduce the unit cost of the components, because bulk discounts tend to be of a higher percentage if the quantity increases. However, this method is risky because there could be a large number of unsold products, hence leading to a significant loss of money.

14. Conclusion

In summary, this report has discussed the development of two prototype APMSs and tested their functionality, performance, and quality. Prototype Idea 2 was shown to be the best prototype because it met all of the user requirements to a high standard. This is because it met all of the design specifications, was shown to operate as intended, had a high accuracy in every reading taken, and was able to operate for over 24 consecutive hours without error. This APMS can be produced within a reasonable time and price range, in addition to having its own unique selling points. For example, it uses easily accessible electronic components, can be built on a breadboard, and uses free open-source software so that hobbyists can easily build and modify the system to fit their own requirements. However, there are some improvements which could have been made, such as adding more error handling for networking and using more accurate sensors. Overall, the APMS achieved all of its predefined requirements, hence making the project a success which can compete with and outclass other APMSs available online in a similar price range. All of the source code, the enclosure design file, and PCB design files are publicly available on GitHub [32].

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