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Personalised Air Quality Monitor using Wearable Sensors

Project Portfolio

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Declaration

I hereby declare that, except where otherwise indicated, this document is entirely my own work and has not been submitted in whole or in part to any other university.

Signed: .... Date: ....

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***Abstract*— This project details the work completed on the topic of: "Personalised Air Quality Monitor using Wearable Sensors". As air pollution rates increase across the globe, research into the application of wearable sensors and their application in this field can be quite useful to raise an individual's awareness of their exposure to air pollution. While prototyping a system to capture data using these sensors, external factors are considered to monitor the raw data being collected. The approach in this project shows methods of how such a system can successfully be prototyped while maintaining a reasonable level of accuracy.**

I. INTRODUCTION

Reviewing previously published materials relating to Air Quality allows us to garner an understanding of the Key Performance Indicators (KPIs) and the components of Air Quality of most interest in this implementation. This will also give credence to understanding the methodologies different sensors use to measure factors of Air Quality, the accuracy and dependencies associated with them. Using this information, suitable sensors can be selected and used to collect data pertaining to the Air Quality of an area, while also investigating any errors in measurement being presented.

II. AIR QUALITY MONITORING RESEARCH

A. *Air Quality Indicators*

The World Health Organisation (WHO) provide a list of pollutants regarding air pollution and the causes of the release of these pollutants [1]. Different sources of information correlate the list provided by the WHO [2] [3], this can indicate that the list of elements is a good starting point to indicate ambient air quality. The elements indicated are Particulate Matter (PM), Carbon Monoxide (CO), Nitrogen Dioxide (NO2), Sulfur Dioxide (SO2) and Ozone (O3) [1].

PM is characterised quite well in [3] and [2], as particles that are of a specific size. PM of diameter 10µm or less are represented as PM_{10}, whereas PM of diameter 2.5µm or less is represented as $PM_{2.5}$. This is the common notation of representation for PM, the most commonly referenced PM sizes measured are; 10µm, 2.5µm and 1µm. The research performed in [4], shows the different Air Quality Indicators (AQI) scales that allow for representing the raw data on a more user friendly scale the AQI Health (AQIH) scale (Ranges from 1-10, good to bad) is recommended for use.

B. *Sensor Measurement Methodology*

Metal oxide semiconductor (MOS) sensors use the properties of a metal oxide's conductivity to determine the level of oxidizing pollutants in the air. In clean air, the Oxygen will bind with the metal oxide, reducing the free electrons available, thus the conductivity is reduced [2]. Whereas if there are Oxidizing pollutants present, the pollutants will bind with the Oxygen particles freeing electrons in the depletion layer and increasing the conductivity of the material [2]. These sensors have a high level of sensitivity but also are highly dependent upon temperature, as the temperature is a key component of the rate of absorption and desorption in the metal-oxide [5]. This kind of sensor is useful for measuring oxidizing pollutants like; O3, NO2, CO and SO2 [5].

Both [5] and [2] concur that small sensors that don't require user input to measure PM can be done by shining a laser and detecting the light being scattered from that laser using a photodiode. This allows the amount of mass per concentration of the chamber to be calculated. More methods of measuring different contaminants and a deeper look at their mechanism is researched and discussed in [4].

C. *Existing Implementations*

There are existing published papers that explore the topic of Air Quality both as a portable and stationary solution. Papers [6], [7] and [8] provide an insight into the challenges and tasks needing to be addressed when constructing a portable system, such as; cost and size. Each of these implementations are very different from; the contaminants being measured to the communication protocol to retrieve the data (Table 1). Sensor selection for the devices vary from using a Dust sensor [6] to detect PM all the way to designing a new PM detector to minimize the sources of error [8]. This design of a whole new PM detector allows for constructing the sensor in a space efficient manner (40x55x23mm^3) [8]. There are other contaminants that are of relevance when monitoring Air Quality, which is monitored in [7].

Paper	Qualities Monitoring	Communication
[7]	PM2.5, PM10, O3, CO, NO2, Temp, Humidity	Bluetooth, MQTT
[8]	PM2.5, PM10	Bluetooth
[6]	PM2.5, PM1	GSM

Table 1: Comparing Air Quality contaminants being measured and communication system to report data in portable systems

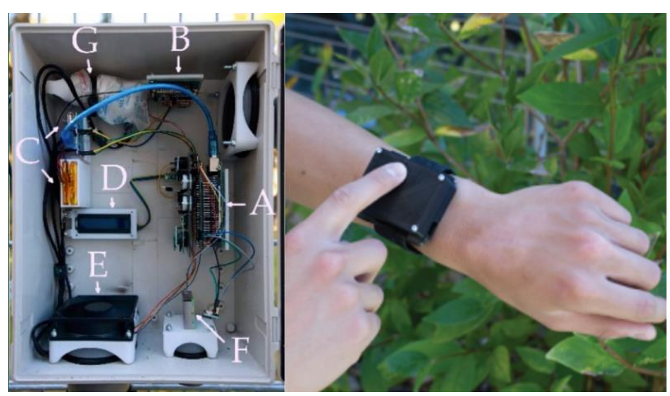

Figure 1: Showing an implementation of a stationary (left) [9] Air Quality monitor compared to a portable one (right) [8].

Papers [10], [9] and [11] present a more stationary approach to monitoring Air Quality. In similar fashion to the portable devices mentioned, each design incorporates different sensors monitoring different contaminants (Table 2). The 3 papers referenced, show a differing approach to the systems constructed. Long term data gathering for analysis [9], a simpler implementation to display to a user the air quality [10] and a device uploading data to a dashboard for ease of access [11].

Paper	Qualities Monitoring	Communication
[10]	Noise, CO2, Benzene, Ammonia	LCD Screen
[11]	CO2, Dust Sensor, Temp, Humidity	LoRa, MQTT
[9]	PM1, PM2.5, O3, CO, NO2, Temp, Humidity	LTE

Table 2: Comparing Air Quality contaminants being monitored and the communication system in stationary systems.

There are commercially available products currently available, those made by Plume Labs and Atmotube can be purchased either as a stationary device or as a portable device as briefly mentioned in [2]. These devices measure different pollutants, depending on the model purchased, many of which monitor PM. In [2], the Air Quality monitor designed and the accuracy it is measuring of each pollutant is discussed giving the insight that PM accuracy is ±10μg/m^3 for the Atmotube device [2].

III. Technical Description

A. Hardware Selection

The major sectors in selecting the components to be used were; air quality sensors, motion sensors, microcontroller unit, wireless communication method. Taking the research outlined in Section: II. Air Quality Monitoring Research, it was decided the main contaminant to monitor is PM_{10} and $PM_{2.5}$, while it also being desirable to monitor CO and NO2 which is the approach in other implementations [7] [8].

For the PM detector, it was decided that obtaining the Sensirion SPS30 was suitable, this is an optical PM detector based upon laser scattering as mentioned in Section: B. Sensor Measurement Methodology. This device can be used in either a UART or I2C configuration, when in active measurement the current consumption is approximately 60mA while in idle current consumption is less than 6mA [12]. These features along with the size of the device being: 41x41x12mm^3 [12], makes for a suitable selection. This device was used or referenced in [2], [9] and [13].

For information on gaseous contaminants, it was decided to use a MOS based sensor, an affordable solution that was easily attainable was the MiCS family of devices, variant 2714 or 4514. These devices were also used both in [9] and [7], which are quite a similar implementation to this design. DFRobot construct a breakout board using the MiCS devices breaking out an I2C peripheral to gather the relevant data, the SEN0377 variant using the MiCS-4514 device was selected. Appendix D delves into further detail surrounding the selection of the sensors [14].

When considering the mode of wireless transmission of the gathered data, Low Power Wide Area Networks (LPWANs) and Bluetooth were heavily considered as both are used in different implementations already existing ([11] and { [7], [8]} respectively). In researching both technologies, the advantages offered by Bluetooth over LPWAN, which being: larger data transfer, faster update rates and unlimited packets being sent, made for a more suitable solution. The LPWAN protocols offer a far better performance in range of transmission and power consumption, but with the dawn of the BLE (Bluetooth v4.0) and Bluetooth v5.0 power consumption has decreased significantly through clever techniques in packet transmission as mentioned in [15]. These developments have made Bluetooth a desirable choice for close range, low power transmission of data which is evident through the industry adaptation of the protocol, whereas LPWAN is more applicable in longer transmission distances and smaller packets.

The selection of the MCU and motion sensors tie together, when researching a suitable platform to use, an option provided by STMicro incorporating facets of the design choices for this project make it a suitable choice. The STMicro SensorTile incorporates a 3-axis accelerometer, magnetometer, and gyroscope interfacing with a low power STMicro 32-bit MCU [16]. This board also incorporates a BLE network processor along with an embedded antenna and filter. This is all packed into a small PCB (13.5x13.5mm^2) [16], this board comes with larger cradle boards that allow for easier programming and use of peripherals (Figure 3). A block diagram of the design of the SensorTile board is shown in Figure 2, although this diagram omits the temperature sensor that is on board. Appendix D discusses the functionality and suitability of this selection to the project in further details [14].

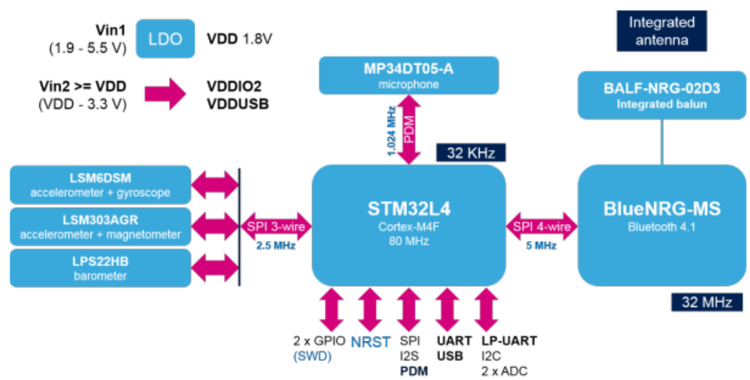

Figure 2: Block diagram of STMicro SensorTile board (STEVAL-STLCS01V1) [16]

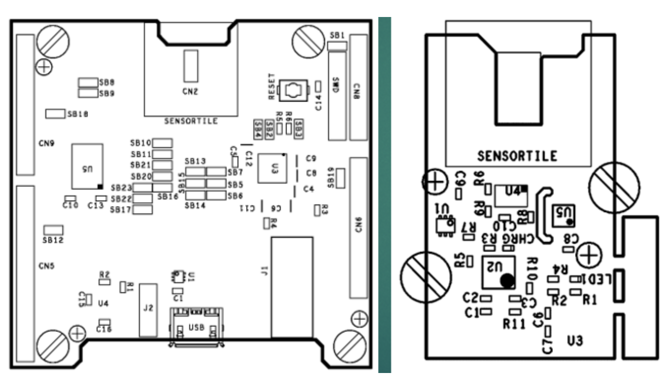

Figure 3: The 2 cradle PCBs provided with the SensorTile kit [16]

B. Programming

The board selected has a software package provided that allows for a head start on the programming of the firmware of the device [17]. This software package sets up the BLE communications and makes the board available for connection, while also setting up the communications with all on-board sensors. To use this board to interface with the external Air Quality sensors selected, the I2C interface is needed to be setup within this program. A driver for the SPS30 device to correctly send commands to setup the sensor and retrieve the data is put in place by Sensirion [18], while the MiCS device has a generic driver that requires some altering to use within the STMicro platform [19]. After setting up the communications with the sensors and the BLE device, a blue LED is lit signifying the device is ready to connect, the sleep time is altered for ease of use to collect data (increased from 20s to 2000s). When connected with an external device the sensor system will not sleep unless disconnected and the timeout is reached. When retrieving the data, the motion sensors data are transmitted every 50ms, whereas the environment and air quality data is transmitted at a far slower rate.

The BLE setup has a variety of GATT characteristics setup and ready for use and update at different rates, these characteristics allow a paired device to request data relating to the characteristic be sent and then listen to the incoming data [20]. It was decided for data collection purposes it was best to use a BeagleBone (BB) with a Bluetooth adapter to use the Linux GATT tools to interact with the BLE device and retrieve and save the necessary data [21]. A useful tutorial from UCLA shows how to use the GATT tool in a BB to correctly interact with the characteristics of the SensorTile [20]. The motion characteristic was altered to also return the environment and air quality data being retrieved from the SensorTile, so only one characteristic is required to be written to in order to obtain the desired data.

C. Data Capture and Analysis

To capture data that is of relevance to the project, it was decided to gather data near existing EPA Air Quality stations [22] to provide a reference measurement to that being gathered, similarly to the testing done in [6]. A major drawback of the reference measurements performed by the EPA station is that each measurement that is published online is an average over an hour period. To counteract this issue, measurements will have to be performed over a reasonable length of time (~20 minutes) [23].

With this pretext of the conditions for data collection presented, this will be done under 2 different conditions:

1. Stationary – Device is completely stationary.
2. Motion – Device will be placed in motion, i.e., walking with the device in hand.

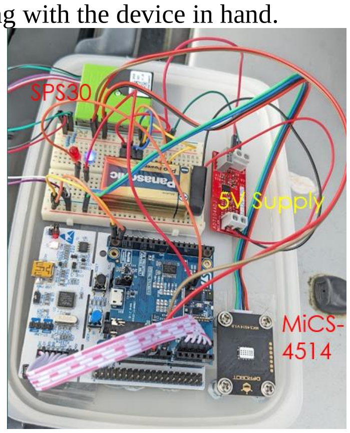

Figure 4: SensorTile board setup with Air Quality sensors for Data Capture

Figure 4 shows the device setup for data collection to be performed. The collected data is then converted from the raw hexadecimals recorded and parsed and stored in a csv file format for further analysis using Python. The collected data and reference measurements can then be used to analyse and define any measured dependencies or account for errors through filtering mechanisms like a moving average filter.

D. Hardware Design

To format the hardware into a smaller form factor, a PCB development cycle was planned to house the units. This design was modelled after the smaller cradle board shown on the right side of Figure 3 [16]. This gave an insight into suitable components for the linear regulator (LDK130 used instead of LDK120), battery charger and fuel gauge (STBC08, STC3115 respectively) used that will work with the existing code [17] [16]. Along with this, pin headers were placed to allow for connection to the MiCS-4514 sensor and the SPS30 sensor through I2C peripherals. This design also adds 2 on board LEDs to signify if ready to be connected or an error in communications with Air Quality sensors.

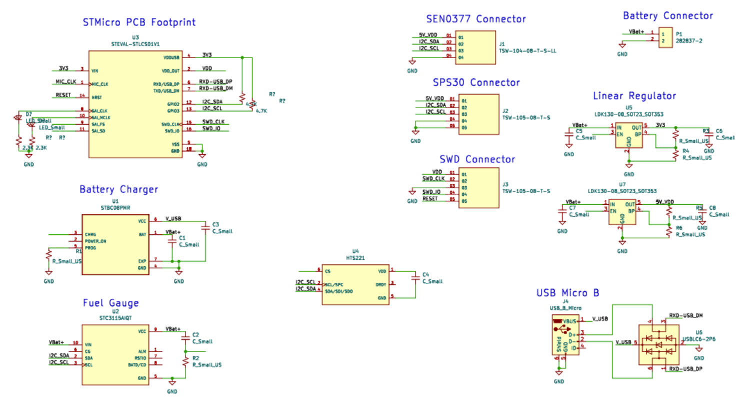

Figure 5: Schematic of PCB Designed

This PCB design is compact into a spacing of less than $27x40mm^2$ (Figure 6). This allows for easier connection to the Air Quality sensors while also making the design much smaller and without the need for an external 5V supply. The deciding size constraint on length and width of the enclosure needed is still the SPS30 sensor ($41x41x12mm^3$) [12]. This is discussed in further details in Appendix D [14].

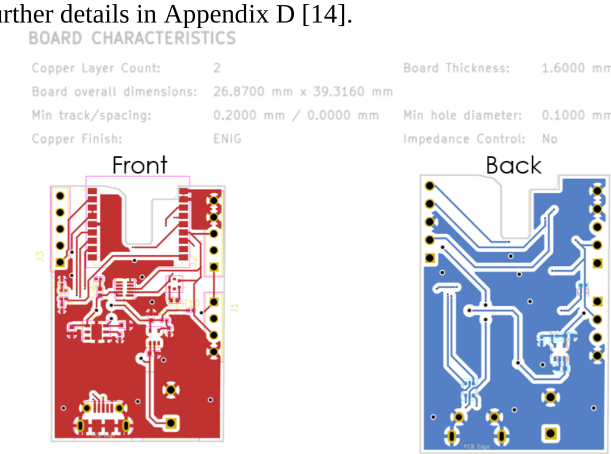

Figure 6: Front and back of PCB layout with thickness, sizing, finish and spacing information

IV. Results Obtained

Data collection was performed in 2 locations near EPA monitoring sites; near Heuston Station, Dublin (Station 57) and in Birr, Co. Offaly (Station 79) [22]. The selected stations provide live information updated every hour. The data collection outlined does not include the collection of information on gases in the area, unfortunately the device being used (MiCS-4514) was damaged and is not reporting any detected gases. Plots shown depict the PM data gathered over a period of time against motion (accelerometer, gyroscope or magnetometer) or environmental (temperature, pressure) data. The plots also have the average PM measured depicted using dashed lines. For reading on data gathered at the Birr site and the relevance of said data to the design process see Appendix E in [24].

A. Heuston Station Data Collection

Data collection was performed at the Heuston site, data gathered was done with a 500ms sample time and with a 5s sample time as well. These measurements were performed for ~20 minutes, while stationary and in motion. Figure 7 shows data gathered at Heuston station, being reported by the EPA as {4.77, 3.15} (Displayed in format of: {PM_{10}, $PM_{2.5}$} ($\mu g/m^3$)) [23] at 13:00 while the average recorded values by the SPS30 device was {1.52, 1.49}.

Data presented in Figure 8 was collected at the Heuston station site at 17:50 with an environmental data update rate of 5s over an approx. 10-minute period. The data displayed in Figure 9 was captured while the device was in motion (Walking with it in hand), while also utilising a 5s environmental data update time. The data interpretation involved clearing outliers causing the plot to be unreadable if not taken out. An outlier was detected if the change in PM is greater than 100 $\mu g/m^3$ in one step, clearly indicating an error this is removed and replaced with the previously recorded result. Errors recorded were also indicated in the temperature and pressure extreme readings. The error detected was caught in real time, being flagged through an LED indicator but no action to curtail it is put in place.

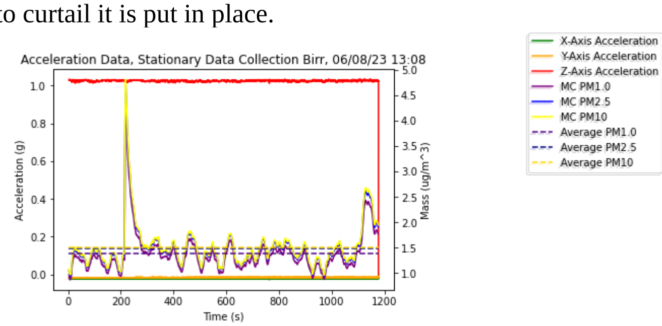

Figure 7: Heuston station data collection accelerometer and air quality data, 500ms sample time for air quality and environmental data measured {1.52,1.49} (Mislabelled title as Birr)

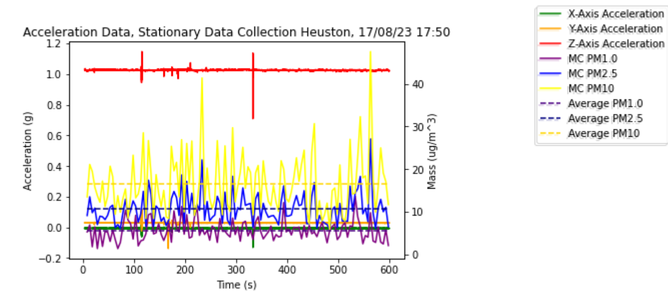

Figure 8: Heuston station data collection accelerometer and air quality data, 5s sample time for air quality and environmental sensors {16.61, 10.73}

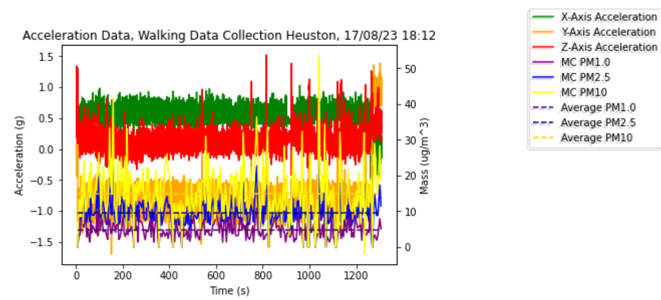

Figure 9: Heuston station data collection accelerometer and air quality data, 5s sample time Air Quality sensors while in motion {14.93, 4.7}

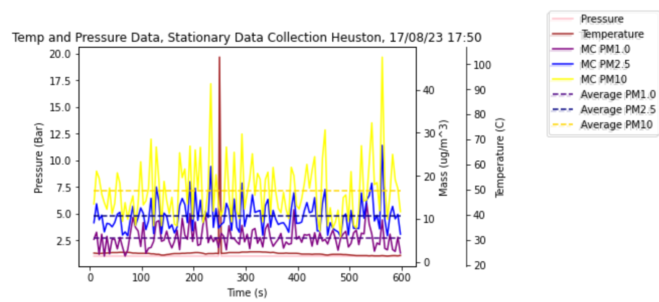

Figure 10: Temperature and Pressure plotted against Air Quality data recorded {16.61, 10.73}

Using a running average over the last 5 samples to smooth out spikes and errors was tested. This implementation did have the desired smoothing effect while also maintaining a similar average PM reading so as not to disturb the overall data collection. The AQIH as discussed in detail in [4] was also calculated every minute and placed on the same plot as the moving average (Figure 11).

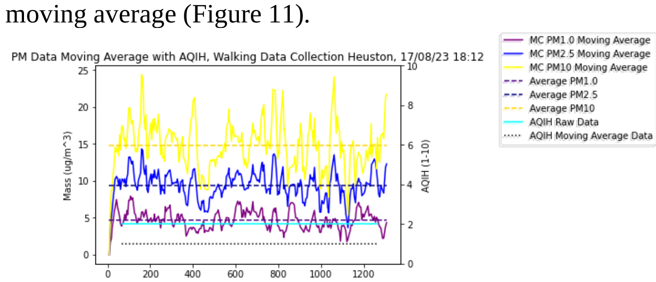

Figure 11: Implemented moving average filter on the acquired data, also including the average PM values over this period and the AQIH, all plotted against time elapsed.

V. Analysis

There are many sources of error in the testing of the device under the experiment conditions, some of these sources are measured, like temperature drift or motion, while some of these are unmeasured like individual behaviours contributing to a localised degradation of Air Quality (Smoking). Some other external factors include the housing constructed for the experiments displayed in Figure 4, although this setup proved be stable. The wiring of this setup using jumper wires and a breadboard was done so without care of parasitic interferences on the bus lanes but wired for ease of probing to analyse any errors.

In spite of the sources of error, the measurements performed and shown in Figure 7, Figure 8 and Figure 9 depict the SPS30 sensor performing within the bounds of a 10µg/m^3 accuracy as is the specification of the device [12] and of an Atmotube product [2]. The results gathered on the final day of testing (17/8/23 - Figure 8, Figure 9, Figure 10) show a good correlation to the measured EPA data. The difference in the measurements is shown in Table 3, this table shows that the data gathered proves to be accurate to the standard set by the industry in Atmotube device [2].

		EPA		**Measured Data**	
Date	**Time**	**PM10**	**PM2.5**	**PM10**	**PM2.5**
17/08/2023	17:00	14.94	9.39	16.61	10.73
17/08/2023	18:00	15.01	9.48	14.93	9.51

Table 3: Reference measurements from EPA shown alongside measured values.

Using a moving average filter to smooth out the data allows for spikes in readings to be minimized, Figure 11 shows a max peak of approx. 25µg/m^3 whereas for the same dataset in Figure 9 this was shown to be in excess of 50µg/m^3. This smoothing of the data allows for more accurate measurements, limiting the effects of a sudden change in measured PM. Although, there appears to be no hugely significant difference in readings when the device is stationary or in motion, errors in readings of the environmental or motion sensors can provide an indicator to a potential error in reading of PM. The sensors on board should not be exhibiting any faults when reporting data, if there are faults being exhibited, e.g. a sharp change in pressure or temperature measured (Figure 10) or a sudden accelerometer change when being stationary for an extended period of time (Figure 7).

Although discussed as an optimal way to represent the raw data gathered in [4], the AQIH has not been of main focus during the Results gathered, it is worth mentioning that with the data gathered the AQIH levels are at a 1 or 2 consistently. This is shown in more detail in Appendix E [24]. When the device is monitoring the air quality while in motion this does not appear to result in a major effect on the readings being gathered compared to the data gathered while stationary, rendering the need for motion sensors in such a system unnecessary.

The gathered data, interestingly shows an increase in air pollution during peak commuting times, Table 3 shows data gathered at 17:00 and 18:00 during a weekday at a train station. This location incurs a lot of traffic to commuters and individuals travelling to Dublin from elsewhere in the country. This data gathered in comparison to the data shown in Figure 7 at 13:00 on a Sunday shows a significant drop in the pollution an individual is exposed to.Figure 7

VI. Conclusion

Overall constructing an Air Quality monitor allowed for great development of knowledge in the topic of air pollution, the harmful effects and causes while also learning about the best suited methods to measure the pollutants. Through the development of this project, it is noted that sensor selection is critical to the reliability of the implementation, as the MiCS-4514 sensor used was easily damaged and unable to continue to be used. The selection of the SPS30 sensor from Sensirion provided a platform to make reliable measurements consistently throughout the development.

It is of note that with the data collection performed and the data collected by the EPA [23], it is clear that while the air quality in Ireland overall is deemed to be of good quality at times of rush hour traffic in Dublin the air quality can take a significant dive. This may warrant an individual's desire to monitor the air quality surrounding them.

The testing completed to verify the performance of the device successfully displays the accuracy of the measurements being measured in accordance with the reference measurements from the EPA stations data. With the knowledge that the reported data is in line with the reference data, it is still recommended to apply an averaging filter to account for errors resulting in a large spike of data. It is also noted that motion has not proved to have a major impact on the reported Air Quality values, a further PCB revision would allow for an even smaller implementation than suggested, for more information this is discussed in Appendix D [14]. Finally, when representing the data to a general-purpose user it is best to use a simple to comprehend scaling which is why the AQIH scales are recommended for use [4].

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31] S. Jiyal and R. K. Saini, "Prediction and Monitoring of Air Pollution Using Internet of Things (IoT)," in *International Conference on Parallel, Distributed and Grid Computing (PDGC)*, Waknaghat, India, 2020.

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Personalised Air Quality Monitor using Wearable Sensors

Appendix A
Literature Survey of Air Quality Monitoring

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August 2023

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Appendix A

***Preface* – The listed Literature Survey differs from the originally submitted Literature Survey. Changes were made in accordance with feedback given after the original marking; subjective opinions describing papers were removed, a discussion of wireless communication methods is now included, a deeper critical analysis of existing implementations is included. As well as this, small grammar mistakes were corrected.**

***Abstract*— This literature review has been written to discuss the currently available articles and journal publications that are relevant to this master's project: "Personalised Air Quality Monitor using Wearable Sensors". This is done by reviewing the available literature that discusses and defines the pollutants relevant when defining air quality. Investigating the best methods to measure these pollutants and the best way to represent the data gathered. Finally, this will review some similar implementations to that being constructed for this project.**

A-I. Introduction

This paper reviews previously published materials available that are in relation to the topic of this Masters' project: "Personalised Air Quality Monitor using Wearable Sensors". Air quality has always been important since the advent of the Industrial Revolution, where there was intense smog descended upon cities due to the combustion engines in manufacturing plants. The emissions from combustion engines are a clear contributor to outdoor air pollution but there are other elements that define the pollution levels of an area, whether indoor or outdoor.

As governments began to regulate the emissions of gases and particles that contribute to air quality, this issue has not been at the forefront of the public. This is partially due to the inability to see the everyday effects that this has on us or even that, depending on where a person lives, may no longer see smog. Despite this not being as prevalent in our lives through air pollution not being visible in many areas of the world, it still can have a deadly effect on our health. The health effects the differing pollutants may have, is briefly outlined later in Figure 12.

It has been decided that the focus of this project is the system design and implementation of a "Personalised Air Quality Monitor using Wearable Sensors"; this will involve the careful selection of components to be used, implementing their use to accurately measure and represent the KPIs. The main materials being discussed in this Literature Review are in relation to defining the aspects of Air Quality, the best way to represent the results, methods to measure these indicators and any implementations previously used.

A-II. Review and Analysis of Prior Work

As stated in the introduction and abstract of this paper, the different aspects of Air Quality and measurement methods will be discussed. This is further broken down into Air Quality Indicators, Measurement Methods, and Current Implementations.

A-A. Air Quality Indicators

The World Health Organisation (WHO) provide a list of pollutants regarding air pollution and the causes of the release of these pollutants [1]. Different sources of information correlate the list provided by the WHO [2] [3] this can indicate that the list of elements is a good starting point to indicate ambient air quality. The elements indicated are Particulate Matter (PM), Carbon Monoxide (CO), Nitrogen Dioxide (NO2), Sulfur Dioxide (SO2), Ozone (O3) [1]. These pollutants have different concerns for the health of humans, the snippet in Figure 12 shows the health effects listed in [3].

Air Quality Guidelines and Standards, Table 5 Summary information on criteria air pollutants regulated as NAAQS[a] by the USEPA

Pollutant	Sources	Key effects of concern	Subpopulations of concern
Ozone	Photochemical oxidation of nitrogen oxides (primarily from combustion) and volatile organic compounds (from stationary and mobile sources)	Decreased pulmonary function, lung inflammation, increased respiratory hospital admissions	Children, people with preexisting lung disease outdoor-exercising health people
Nitrogen dioxide	Photochemical oxidation of nitric oxide (primarily from combustion of fossil fuels) and direct emissions (primarily from combustion of natural gas)	Respiratory illness, decreased pulmonary function	Children, people with preexisting lung disease
Sulfur dioxide	Primarily combustion of sulfur-containing fossil fuels; also smelters, refineries, and others	Respiratory injury or death, decreased pulmonary function	Children, people with preexisting lung disease (especially asthma)
Particulate matter	Direct emission of particles during combustion, industrial processes, gas reactions and condensation and coagulation natural sources	Injury and death	Children, people with preexisting heart and lung disease
Carbon monoxide	Combustion of fuels, especially by mobile sources	Shortening of time to onset angina and other heart effects	People with coronary artery disease
Lead	Leaded gasoline (prior to phase-out in gasoline);point sources such as Pb mines, smelters, and recycling operations	Developmental neurotoxicity	Children

Figure 12: Sources and health effects of the pollutants outlined (Includes lead) [5]

PM is characterised quite well in [3] and [2], these are particles that are of a specific size. PM of diameter 10μm or less are represented as PM_{10}, whereas PM of diameter 2.5μm or less is represented as $PM_{2.5}$. This is the common notation of representation for PM, the most common PM sizes; 10μm, 2.5μm and 1μm. The sizes of PM can have different health effects, [2] provides an excellent diagram displayed in Figure 13 that shows the depth different PM sizes can be deposited within the respiratory system.

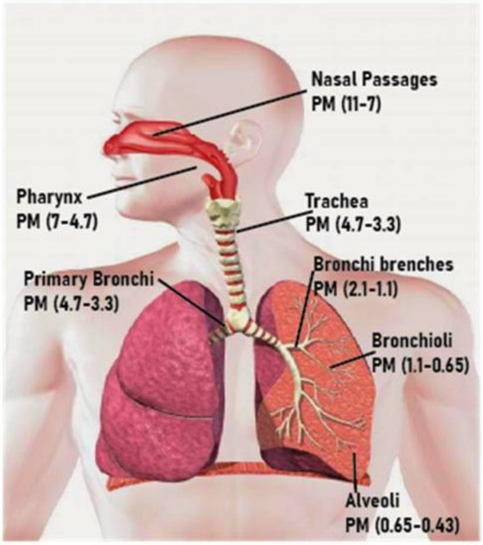

Figure 13: Deposition location of PM according to size [2]

The paper written in [2] provides an overview of the different pollutants, their sources and health impacts. This paper does concur with the list of pollutants provided by the WHO [1] while also looking at Volatile Organic Compounds (VOCs). This addition to a list of pollutants is justified, USA's Environmental Protection Agency (EPA) also does indicate this as a pollutant [25] and defines it as "high vapor pressure and low water solubility" [25]. VOCs are an indicator of indoor air quality rather than outdoor air quality; this is due to the production of VOCs outdoors is regulated by a governing body as they contribute to smog production (The level of regulation is dependent upon the country) [26].

The Air Quality Index (AQI) is an indicator that is used by national health departments to convey to the public the quality of the country's air. Different methods of calculating AQI has led to different standards for this indicator. The differing standards of AQI has led to different scales to represent the raw data. Due to this, companies that make commercially available air quality monitoring devices (Atmotube and Plume Labs) have defined their own version of AQI. In [27], the different standards defined by; Canada, USA, Europe, United Kingdom, Australia, South Korea, Singapore, Hong Kong, China and India are listed showing how to interpret the scales of the measurements and the pollutants being represented. These scales all differ significantly, Europe's Common AQI (CAQI) is measured on a scale of 1-100 which is intuitive and easy to interpret whereas USA's scales are from 0-300+ and are not as intuitive to read [27].

There are other interpretations of AQI not listed by [27], such is the AQI Health (AQIH) defined by the Irish government agency Environment Protection Agency (EPA) [28]. There are a set of tables given to convert the raw data recorded into the corresponding value for AQIH. This is represented on an easy to interpret scale of 1-10 ranging from Good to Very Poor [28]. The tables shown in Table A-4 and Table A-5, show the levels of each referenced pollutant to the AQIH scale. The scales being broken into brackets for each pollutant makes this easy to calculate if a subset of pollutants being monitored.

Band	Index	O3 (μg/m^3)	NO2 (μg/m^3)	SO2 (μg/m^3)
Good	1	0-33	0-67	0-29
	2	34-66	68-134	30-59
	3	67-100	135-200	60—89
Fair	4	101-120	201-267	90-119
	5	121-140	268-334	120-149
	6	141-160	335-400	150-179
Poor	7	161-187	401-467	180-236
	8	188-213	468-534	237-295
	9	214-240	535-600	296-354
Very Poor	10	241 +	601+	355+

Table A-4: AQI Table provided by Irish EPA continued [28]

Band	Index	PM$_{2.5}$ (μg/m^3)	PM$_{10}$ (μg/m^3)
Good	1	0-11	0-16
	2	Dec-23	17-33
	3	24-35	34-50
Fair	4	36-41	51-58
	5	42-47	59-66
	6	48-53	67-75
Poor	7	54-58	76-83
	8	59-64	84-91
	9	65-70	92-100
Very Poor	10	71+	101+

Table A-5: AQI Table provided by Irish EPA continued [28]

A-B. Methods of Measuring Air Pollution

The different elements that constitute air pollution listed above can be represented in different ways: parts per million/billion (ppm or ppb) or in mass per volume (μg/m^3). There are different measurement methods available to measure the different pollutants, which may result in differing formats. In [2] the measurement methods are discussed and gives a good overview of different sensor types for both gases and PM. Likewise in [5], also gives an in-depth view of the available methods to measure gases and PM in greater detail. Both sources point out the positives and negatives of each relevant measurement method.

Metal oxide semiconductor (MOS) sensors use the properties of a metal oxide's conductivity to determine the level of oxidizing pollutants in the air. In clean air, the Oxygen will bind with the metal oxide, reducing the free electrons available, thus the conductivity is reduced [2]. Whereas if there are Oxidizing pollutants present, the pollutants will bind with the Oxygen particles freeing electrons in the depletion layer and increasing the conductivity of the material [2]. These sensors have a high level of sensitivity but also are highly dependent upon temperature, as the temperature is a key component of the rate of absorption and desorption in the metal-oxide [5]. This kind of sensor is useful for measuring oxidizing pollutants like; O3, NO2, CO and SO2 [5]. These sensors are particularly useful if used in conjunction with a temperature and humidity sensor to monitor changes in temperature so not to misinterpret higher readings when the temperature is increased.

Non-dispersive infrared (NDIR) sensors take advantage of Beer-Lamberts' equation to use an IR light source and a photodetector to be able to determine the concentration of a gas according to the absorption of the IR light [5] [2]. This is a cheap sensor that has low power consumption, making it ideal for an application in a battery powered system, this is commonly used to measure CO2 [5].

Both [5] and [2] concur that small sensors that don't require user input to measure PM can be done by shining a laser and detecting the light being scattered from that laser using a photodiode. This allows the amount of mass per concentration of the chamber to be calculated. This is represented visually in Figure 14.

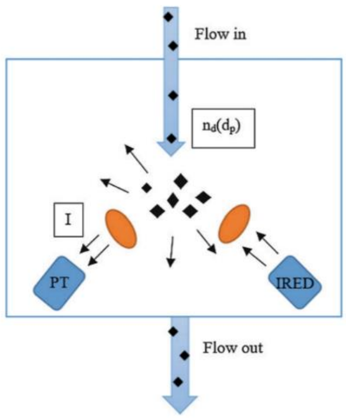

Figure 14: Image of inner working of PM detector using a laser and photo detector [13]

A-C. Current Implementations

There are some existing implementations that are somewhat in-line with the desired outcomes of this project. As mentioned, Plume Labs have created a portable Air Quality monitor that is capable of monitoring different pollutants and displaying the results in the form of their own AQI. Also mentioned is Atmotube's commercially available products, similarly they have a product available for users to monitor different pollutants and display the resulting measurements in terms of its' own Air Quality Score (Scored 0-100, where 100 is good and 0 is bad). Both products are constructed to perform the desired tasks as this project and appear to be designed with space constraints in mind as well as power consumption.

There are numerous published papers and projects that follow along the same lines of this project. There are projects constructed to monitor noise but were not implemented in a method to be portable, like that in [10]. Paper [10] did not offer a reasoning as to why the pollutant SO2 was selected but details the design of the system. There are papers that detail the reasoning behind selecting PM as the focus [6], while also providing a design to monitor said pollutant without mentioning the portability of the system. The design in [6] does select components with sizing as a concern, with selecting the largest component as the Dust sensor to monitor PM (PPD42NS) being a size of 55x45x22mm^3.

In [2], there is a discussion around the works done in the space of monitoring air quality. There is a discussion around the available products like that made by Atmotube and Plume Labs, as well as other research papers that delve into this topic [2]. There are clearly some existing implementations researched and thought through, MyPart have designed a wrist wearable device to monitor PM using a specially designed PM detector for a smaller form factor [2]. This section of the paper provides a view as to what currently exists, and what directions can be taken to develop this project.

A-D. Communication Method

There are many different options available when it comes to communication methods in wearable devices, from; display screens to Bluetooth to Low Power Wide Area Networks (LPWAN). Each communication method has specific use cases, a screen is most useful where most of the processing is being performed at the source of data capture and does not require an external device to perform some processing duties. In applications where the data captured needs to be stored elsewhere and be made accessible a wireless communication protocol such as Bluetooth or LPWAN is more applicable.

Bluetooth is used as a low range wireless communication protocol capable of sending a large amount of data to a device in comparison to packets being sent by a LPWAN protocol, can be seen graphically in Figure 15. The range of Bluetooth is measured in meters, whereas the range of LPWAN devices are measured in 10's of kilometers [29]. Different LPWAN protocols can exhibit differing features, SigFox having a range of 10km/40km, LoRa 5km/20km and NB-IoT 1km/10km (Range referenced as: urban/rural) [29]. To access the data, using a LPWAN protocol would require interacting with a secure server to transfer the data, whereas use of Bluetooth does not require such a transfer.

LPWAN offers significant advantages in low payload long distance transmission, whereas in close proximity to a user Bluetooth is a clear choice to use for this project.

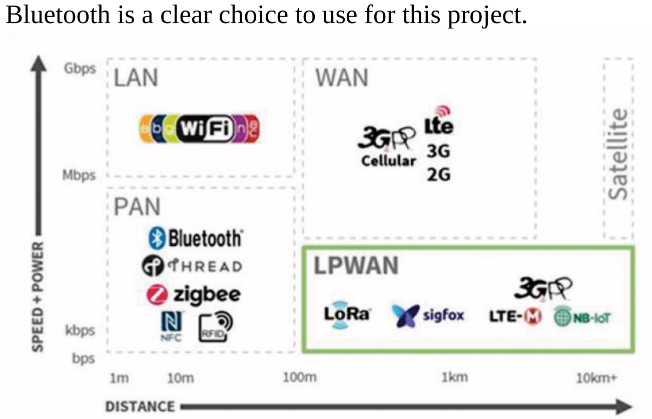

Figure 15: Graphical representation of the wireless communications range and performance

A-III. RELATION OF PRIOR WORK

The reviewed literature has given indications of the directions that may be explored depending on different constraint factors of a system. Space and power being a main constraint points to trying to select efficient devices in a small package size where possible, like that done in [6]. The work monitored through [2] and [6] indicate the main pollutant to monitor is PM, while products available from Plume Labs and Atmotube indicate it is also useful to monitor additional pollutants where possible. Space constraints may have a major effect on the contaminants being monitored. Some of the higher end commercial products available from Atmotube and Plume Labs measure PM and additional contaminants. If this is the case in a given project, it may be best to use a version of AQI that will encapsulate all the measured variables.

Seeing as this project is space constrained, in aiming to use wearable sensors, as well as power constrained as this will need to be portable. It is not best to measure all the pollutants and hence better to use an AQI index that can be calculated with minimal pollutants being measured.

A-IV. Conclusion

Moving forward, it is best to consider PM as the main contaminant to monitor, if spacing constraints permit can also measure different pollutants, like O3 or NO2. As outlined in Methods of Measuring Air Pollution, an AQI that can be calculated with a limited set of pollutants measured is best, the Irish AQIH may be used moving forward. This will also allow for correlation of measurements performed and published by the EPA in Ireland.

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Personalised Air Quality Monitor using Wearable Sensors

Appendix B
Project Design Plan

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Appendix B

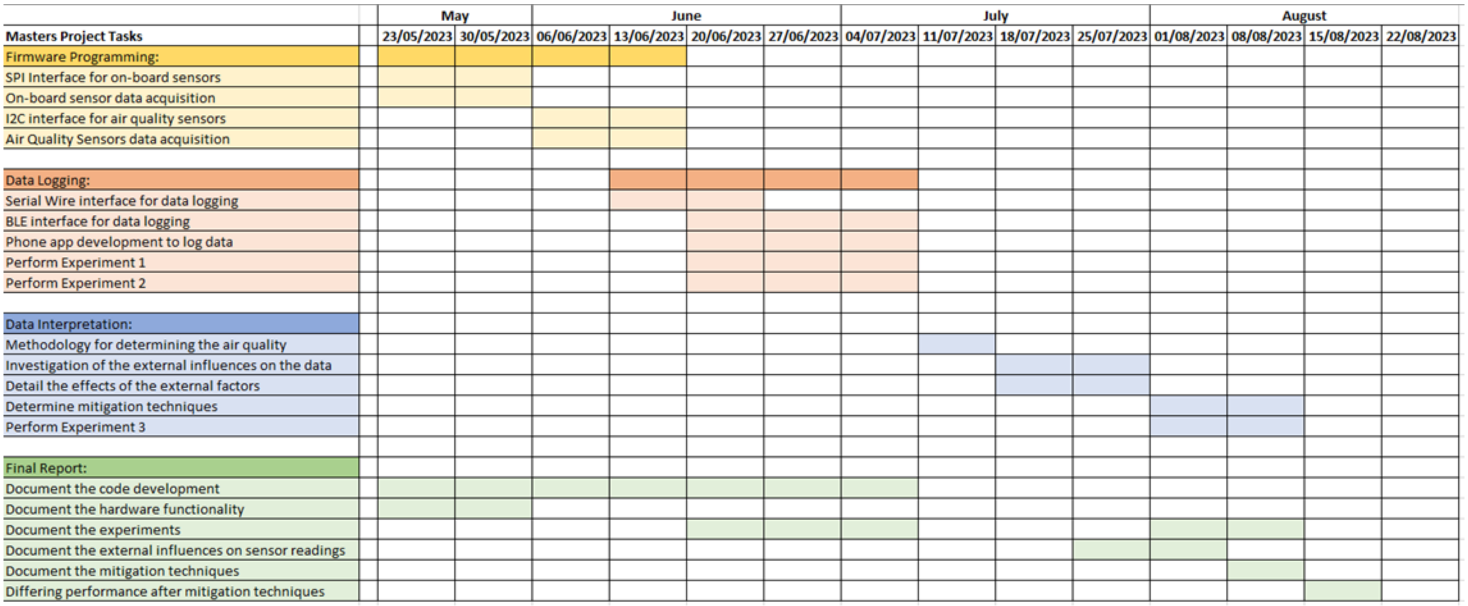

Figure 16: Development plan for the project

B-I. Detailing of Project Progression

At the beginning of the development cycle of this project (start of May) a project plan was put into place, shown in Figure 16. This plan broke down the tasks into 4 distinct sections highlighted in yellow, orange, blue and green with the sections being; Firmware Programming, Data Logging, Data Interpretation and the Final Report. This was done to break the tasks down into smaller tasks to ensure the project timeline was easy to track.

In the plan listed, the Firmware programming was completed late, and this subsequently had a knock-on effect to the Data Logging and Data Interpretation sections. The Firmware programming section was delayed due to issues with delivering components.

The Data Logging was delayed further due to a hardware issue. More specialized soldering equipment than available at DCU was needed to solder an essential board, Analog Device International granted access to use their equipment in their Limerick site. After soldering the board and returning to Dublin, a solder pad tore off needing to be repaired, when preparing to travel down to fix said pad Covid-19 was contracted and the trip was delayed. After recovering from Covid-19 and returning to Limerick it was discovered the board was not fixable and a new board was required. This cycle took >3 weeks to resolve the issue. This also resulted in foregoing the phone app development planned, the timeline allotted toward this development was taken up by solving the issues relating to the hardware and using a Beaglebone to log the data instead. Experiments 1 and 2 were performed, this being collecting data nearby an EPA monitoring station while stationary and while in motion.

Data Interpretation was rushed to be completed in time due to these delays, use of mitigation techniques when measuring the air quality live was not implemented (Experiment 3).

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Personalised Air Quality Monitor using Wearable Sensors

Appendix C
Research Log

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Appendix C

A COMPLETE REFERENCE FOR THE PAPER
[7] G. Girão and H. P. L. de Medeiros, "An IoT-based Air Quality Monitoring Platform," in *2020 IEEE International Smart Cities Conference (ISC2)*, Piscataway, NJ, USA, 2020.
Summary of paper (maximum 100 words)
This paper addresses the issue of Air Pollution by discussing the key indicators of poor air quality and the discussion of designing a system to monitor the Air Quality. There is a discussion around existing implementations before suggesting their own design. This system is designed to be portable and makes use of the LoRa and MQTT protocols to store and distribute the data measured (PM2.5, PM10, O3, CO, NO2, NH3)
How is this paper relevant to solving your project problem or addressing your research question?
The discussion around Air Pollution reinforces the stance taken that PM is the main contaminant of concern, the design of a monitoring system is implemented in a way to ensure for a small device if at all possible. The discussion around the sensors selected for use informs this project problem.
What are the strengths and weaknesses of the solutions/methods/technologies proposed in this paper?
The paper offers good detail in reviewing background research and proposing a new design. The details on why the sensors used were selected is very good, giving great insight into the main goals of the project. The backend structure of how the system works is not explained in easily digestible terms.

A COMPLETE REFERENCE FOR THE PAPER
[10] T. Manglani, A. Srivastava, A. Kumar and R. Sharma, "IoT based Air and Sound Pollution Monitoring System for Smart Environment," in 2022 International Conference on Electronics and Renewable Systems (ICEARS), Tuticorin, 2022.
Summary of paper (maximum 100 words)
This paper is concerned with the design of an IoT system to monitor dangerous gases; NH3, Benzene and CO2. This system is Arduino based and uses an LCD screen to report the AQI level being calculated.
How is this paper relevant to solving your project problem or addressing your research question?
The implementation displayed shows a simple design to measure harmful chemicals, showing the ease of use of some sensors selected like the MQ135.
What are the strengths and weaknesses of the solutions/methods/technologies proposed in this paper?
This paper proposes a rudimentary design of a system to monitor the gases deemed to be harmful, limited Literature Review is reported upon. Despite the drawbacks, it displays the simple ways a system can be put in place while also showing some sensors that are of use.

A COMPLETE REFERENCE FOR THE PAPER
[30] S. Maurya, S. Sharma and P. Yadav, "Internet of Things based Air Pollution Penetrating System using GSM and GPRS," in International Conference on Advanced Computation and Telecommunication (ICACAT), Bhopal, India, 2018.
Summary of paper (maximum 100 words)
This paper delves into the issue of Air Pollution monitoring, specifically designing a cheap reliable sensor node network to monitor CO2, Smoke, Temperature, Humidity and NO. This design incorporates using GPS tracking and GPRS signalling, there is a PCB development that is undergone to house the system design.
How is this paper relevant to solving your project problem or addressing your research question? (maximum 100 words)
This paper is proposing an air pollution monitor that is using a sensor node network, although a variation of an implementation of what is desired here, it is describing the sensors and the process of developing the product which is directly useful to this development. It also dives into another option for wireless communication previously unconsidered
What are the strengths and weaknesses of the solutions/methods/technologies proposed in this paper? (maximum 100 words)
The paper offers great reasoning for the need of such a system ,documents its design well from the sensor selection to the PCB design. The system testing does not have a reference measurement that is validating the accuracy that is being stated in the conclusion.

A COMPLETE REFERENCE FOR THE PAPER
[31] S. Jiyal and R. K. Saini, "Prediction and Monitoring of Air Pollution Using Internet of Things (IoT)," in International Conference on Parallel, Distributed and Grid Computing (PDGC), Waknaghat, India, 2020.
Summary of paper (maximum 100 words)
The paper provides clear reasoning for the need to monitor the air pollution while discussing the reasoning it exists and how it affects people. It also delves into why an IoT system is suitable for this problem before proposing a design using an MQ135 and DSM501A to monitor the Air Quality which would be sent to a secure server. The proposed design is from a block diagram level.
How is this paper relevant to solving your project problem or addressing your research question? (maximum 100 words)
The contaminants mentioned give an insight into what is possible to measure and the sensors that are available to be used to measure them. It also provides good reasoning toward the need to monitor air quality by providing background research into the effects of poor air quality and its causes.
What are the strengths and weaknesses of the solutions/methods/technologies proposed in this paper? (maximum 100 words)
It gives excellent background research into the need to monitor Air Quality while also showing the causes of air pollution. There is only a very brief preview of existing work before proposing it's own solution. The system design leaves a lot to be desired, after sensor selection there is not a huge amount of detail put into place, this also exhibits no validation of its design.

A COMPLETE REFERENCE FOR THE PAPER
[8] R. Tian, C. Dierk, C. Myers and E. Paulos, "MyPart: Personal, Portable, Accurate Airborne Particle Counting," in Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, San Jose, CA, 2016.
Summary of paper (maximum 100 words)

This paper seeks to design a small frame PM device that harbours few sources of error while providing a Bluetooth and app interface to report the data gathered. The extensive research into the topic shows the methods of limiting the errors in the design as well as the design implementations itself.
How is this paper relevant to solving your project problem or addressing your research question? (maximum 100 words)
This design shows the accuracy to strive for in designing a system that monitors PM, while also exhibiting that a device can be designed into a small frame. It also gives in-depth detail of how a PM sensor is constructed.
What are the strengths and weaknesses of the solutions/methods/technologies proposed in this paper?
Excellent review on how PM is monitored and its main sources of error, great design on how to compact a design into such a small lead frame. Introduces a validation study to ensure good quality measurements are performed. Does not consider any other pollutants in its design.

A COMPLETE REFERENCE FOR THE PAPER
[11] M. Y. Thu, W. Htun, Y. L. Aung, P. E. E. Shwe and N. M. Tun, "Smart Air Quality Monitoring System with LoRaWAN," in 2018 IEEE International Conference on Internet of Things and Intelligence System (IOTAIS), Bali, 2018.
Summary of paper (maximum 100 words)
Providing a background into the need for monitoring Air Quality, addressing the need using a LPWAN communication system along with sensors to monitor temperature, humidity, CO2 and dust while uploading the data to a server displaying the data on a dashboard.
How is this paper relevant to solving your project problem or addressing your research question? (maximum 100 words)
It is showing a design of an entire front to back-end system resulting in the data being displayed on a dashboard. It is exhibiting a system that employs the use of a LPWAN to send the data to a secure server, which is an option for this project.
What are the strengths and weaknesses of the solutions/methods/technologies proposed in this paper?
It shows the design of the entire system and shows the data being displayed on the dashboard, but there appears to be no validation of results shown.

A COMPLETE REFERENCE FOR THE PAPER
[6] G. O. Avendano, J. C. Dela Cruz, A. H. Ballado, L. G. Rommel Ulyzes, A. C. Paras Atienza, B. J. G. Regala and R. C. Uy, "Microcontroller and app-based air quality monitoring system for particulate matter 2.5 (PM2.5) and particulate matter 1 (PM1)," in IEEE 9th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment and Management (HNICEM), Manila, Philippines, 2017.
Summary of paper (maximum 100 words)
This paper concerns the development of a measurement apparatus to monitor air quality, clearly indicating PM is of main concern to monitored. The system employs the use a GSM module to send and receive data to be stored in a cloud and retrieved via an app. There is a clear validation and calibration study that occurs to show its working correctly
How is this paper relevant to solving your project problem or addressing your research question? (maximum 100 words)
An end to end solution including, while providing reasoning for the monitoring of PM and the method of validation, giving credence to the validation of data collected planned for this project as well as focusing upon PM.

What are the strengths and weaknesses of the solutions/methods/technologies proposed in this paper? (maximum 100 words)
Shows the validation of data being gathered in great deal, even detailing the outcome of the regression of the data collection performed. But this system does not show any concern for any other contaminant.

A COMPLETE REFERENCE FOR THE PAPER
[9] P. Gaebel, C. Koller and E. Hertig, "Development of Air Quality Boxes Based on Low-Cost Sensor Technology for Ambient Air Quality Monitoring," Sensors, May 2022.
Summary of paper (maximum 100 words)
This paper delves into the design of a stationary air quality monitoring system. This design focuses upon the data acquisition and characterising the sensors performances to determine which sensors of that selected are the most useful for this kind of an application. The contaminants being monitored are PM1, PM2.5, O3, CO, NO2, Temp, Humidity.
How is this paper relevant to solving your project problem or addressing your research question?
This gives an insight into the available sensors in the market and an application of how to use said sensors for their purpose, while also displaying how accurate they are. This gave the recommendation of using the SPS30 device for this project, the MiCS-4514 device was also used although used was not heavily endorsed in this study.
What are the strengths and weaknesses of the solutions/methods/technologies proposed in this paper?
The paper does a good job in designing the system as a whole, from the electronics to the mechanical fitting of the components in the box, the examination of the collected data is also done excellently. Overall ,the paper is constructed excellently and showcases a great design with a good Literature review justifying the choices made.

A COMPLETE REFERENCE FOR THE PAPER
[2] S. Bernasconi, A. Angelucci and A. Aliverti, "A Scoping Review on Wearable Devices for Environmental Monitoring and Their Application for Health and Wellness," MDPI Sensors, vol. 22, no. 16, p. 5994, 2022.
Summary of paper (maximum 100 words)
This paper provides an overview of contaminants that define Air Pollution and subsequently Air Quality, it goes on to define the different measurement methods to detect the different contaminants and overviews various different implementations to monitor Air Quality, wether it be commercial products or research papers published.
How is this paper relevant to solving your project problem or addressing your research question?
This gives an insight into the available methods in monitoring Air Quality as well as the contaminants that are of note in this area. It provided a starting point of where to look when researching these topics to implement a design.
What are the strengths and weaknesses of the solutions/methods/technologies proposed in this paper?
The paper does a good job giving an overview of the available products, measurement methods and sensors available, it does provide a heavily critical approach when presenting this information. It also provides a very good scope of the contaminants that are of note.

Paper Ref	Qualities Monitored	Stationary/Portable	Communication Protocol	Sensors
[7]	PM2.5, PM10, O3, CO, NO2, Temp, Hum	Portable System	Bluetooth/Wifi, MQTT	MQ131, PMSA003, MiCS-6814, DHT22
[10]	Noise, CO2, Benzene, Ammonia	Stationary	LCD Screen	MQ135
[30]	CO, NO, Smoke, Temp, Hum		GSM/GPRS	MQ135, MQ2
[31]	NH3, C6H6, Smoke, CO2, PM1, PM2.5			MQ135,DSMM501
[8]	PM2.5, PM10	Portable System	Bluetooth	Custom design
[11]	CO2, PM, temp, humidity	Stationary	LoRa, MQTT	Telaire Air Quality Evaluation Kit, T6713, SM-PWM-01C, T9602
[6]	PM2.5, PM1	Portable System	GSM	Shinyei PPD42NS
[9]	PM1, PM2.5, O3, CO, NO2, Temp, Humidity	Stationary		BME280, MQ131, MiCS-2714,MiCS-4514, DGS-O3, DGS-NO2, SPS30

Table 6: Research log of Air Quality monitoring developments, showing contaminants of interest, sensors used and communication protocols

C-I. Research Log Detail

The research papers outlined in Table 6 provided an essential insight into the different ways an Air Quality monitor can be constructed. Whether the differences are the contaminants being monitored, the design of the system is to be stationary, the communication method being used, or the sensors used to implement the system. The papers chosen, provide a broad view of how to implement a system allowing for a view of the pitfalls in a system design.

The papers referenced detail the contaminants being monitored, which gives a good guide as to a list of possible contaminants to monitor. Each paper listed has a variety of differing contaminants being monitored, a consistent theme across 6 of the papers is PM being monitored [7] [31] [8] [11] [6] [9]. Through the majority of the papers included in this study monitoring PM (6 out of 8), this does give credence to the idea to focus upon PM monitoring while monitoring gases being secondary.

C-A. Informing Sensor Selections

A paper not shown in the research log (Table 6) reviews multiple designs and implementations to monitor Air Quality [2], in showing the different implementations already in existence it provided an aid to the design process. [2] first introduced the SPS30 device, showcasing its small form factor, when compared to the devices used in [7] [31] [8] [11] [6] to monitor PM it was deemed a more suitable solution due to the size and performance of the sensor. This selection was also justified through the use of it in [9] to monitor PM.

The sensor selection for monitoring available gases was also encouraged through the research performed, the papers shown in Table 6 show a wide variety of different sensors available to monitor a wide variety of gases. While concurring with the findings of the WHO and the Irish EPA in deeming O3 and NO2 to be additional contaminants to be concerned with [4], the cost of the sensor MQ131 which is used in [7] and [9] ruled out it’s implementation while the cheaper MQ135 used in [31] [30] [10] was more difficult to obtain and subsequently ruled out. The family of devices DGS-O3 and DGS-NO2 used in [9] proved too difficult to obtain. While the family of MiCS sensors used in [7] and [9] provided a cheaper solution that was easily available for purchase.

C-B. Presentation of Results

In the papers identified some provided details of their testing procedures [6] [10] [30] [8] [9]., while others did not [7] [31]. Of the papers referenced that did detail their testing procedure, only [6] and [8] showed the measurements being performed against measurements performed by a known source.

Of the testing procedures and results shown, [6] informed the design of the testing structure the most, as using a governmental reporting system to be able to measure against is able to be replicated at ease due to the location of the EPA stations [22]. While possible to use a reference measurement apparatus as done in [8], it was decided to forego this and focus upon testing against the EPA provided stations. This made for an accessible feedback loop of testing the device and making alterations to the system, while also having access to data regarding measured gases.

C-C. Value of Continued Research

The continued reading of research allowed for a greater understanding of the wide range of setups being employed to monitor Air Quality, while also showing to monitor PM a PM detector is not an essential tool to be acquired [8] [11]. While also informing of the difficulties in monitoring gases of interest. This also allowed for expansion of knowledge surrounding different communication protocols [29] [11], while allowing for understanding their applicable use cases. The continued reading has informed the design of the system employed through informing of differing products available to how best to perform the measurements.

School of Electronic Engineering

Personalised Air Quality Monitor using Wearable Sensors

Appendix D
Project Design & Implementation

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Appendix D

This Appendix document details the design choices and the reasoning for selecting of the specific components and design elements employed, this also details the method of the different software packages are employed and the use for them.

D-I. Hardware Component Selection

The component selection can be broken down into subtopics of; Microcontroller (MCU) platform, Bluetooth Low Energy (BLE) interface, Motion Sensors, Power Delivery, Air Quality Sensors.

In deciding upon using a previously unexplored/unused option to broaden horizons and hearing of the easy-to-use Integrated Development Environment (IDE), it was decided to use an MCU from the STMicroelectronics (STMicro) family. Their MCU's are constructed using the ARM architecture, which can employ aggressive power saving features from their low power designs if so desired. The IDE provided by STMicro (STM32 Cube IDE), is built upon the Eclipse environment making for an easy familiarity for users already familiar with Eclipse [32]. The use of an MCU from this family of devices allows for room for learning the features of the IDE and MCU. The 32-bit processors offered can be obtained from the high performance or low power ranges, for this application it is suitable to select from the Low Power family.

With deciding upon the MCU platform, the BLE interface and the motion sensors tie together. This is due to receiving a recommendation of using the STMicro SensorTile if desiring to use the STMicro MCU platform along with motion sensors and a BLE interface [16]. After investigating this suggestion, which has a 3D Accelerometer (LSM6DSM, LSM303AGR), gyroscope (LSM6DSM) and magnetometer (LSM303AGR) along with a barometer (LPS22HB) on a board of size 13.5x13.5mm^2 [16]. The core of this board uses a STM32L476jg, which is a Low Power design based upon the Arm Cortex-M4 architecture [16] [33], this also satisfies the criteria of a low power MCU core. Finally, the board uses a BlueNRG-MS BLE network processor with an integrated antenna to incorporate Bluetooth functionality for this system [16]. The compact SensorTile board (13.5x13.5mm^2) [16] is accompanied with 2 cradle boards (Figure 3) that allow for breaking out peripherals further along with the programming pins [16]. These 2 cradle boards are significantly different, as the smaller cradle requires the SensorTile to be soldered and access to pins of the board is limited through the solder connections, whereas the larger cradle board uses a connector that is on the bottom of the cradle board while also breaking out peripherals to Arduino Uno compatible pins [16]. The larger cradle board can sit onto a Nucleo board that can in turn be used to program the STMicro board (Figure 17).

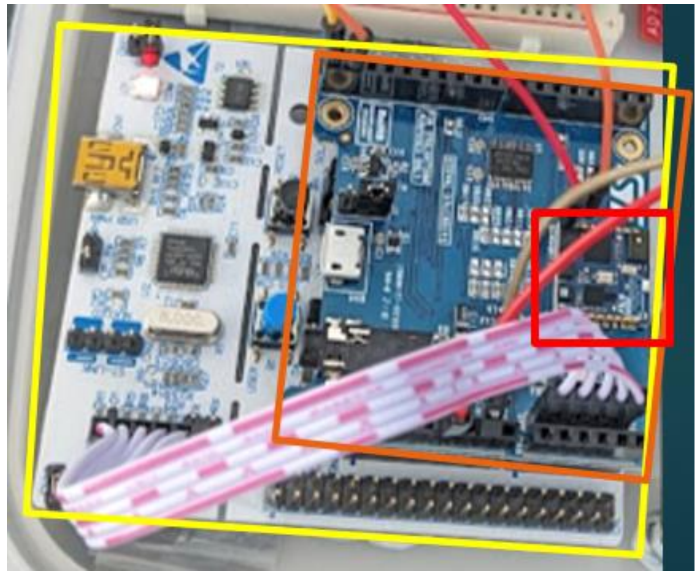

Figure 17: Showing Nucleo, cradle and SensorTile boards. Yellow box is the entire Nucleo board, orange box is the large cradle board, red box shows the SensorTile.

With the selection of the MCU, motion sensors and BLE interface completed the air quality sensors needed to be selected. For this the available peripherals are needed to be identified, Figure 18 shows the peripherals that are made available at the header pins. Showing an SPI, UART and I2C interface available along with a pair of GPIO pins. The Air Quality sensors selected ideally will use one of these protocols to ensure for ease of use with the SensorTile but this is not a deciding factor, if the desired sensors do not use such interfaces a different device (Arduino) can be used to act as an I2C slave to send the sensor data to the SensorTile (Figure 19, Figure 20). The need for an Arduino (Figure 20) can be eliminated through a PCB redesign exposing more peripherals to connect to the Air Quality sensors.

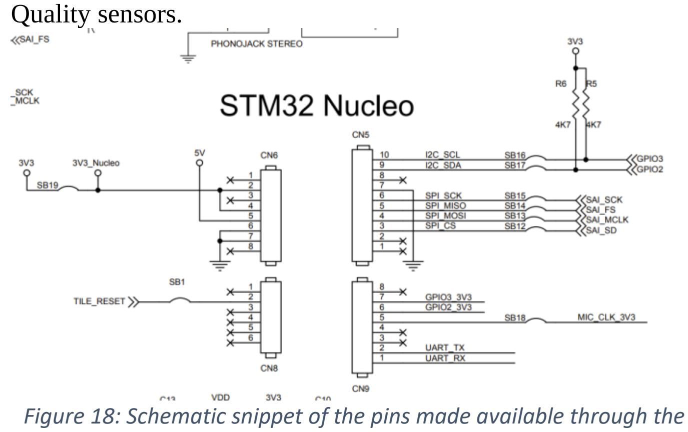

Figure 18: Schematic snippet of the pins made available through the header pins [16]

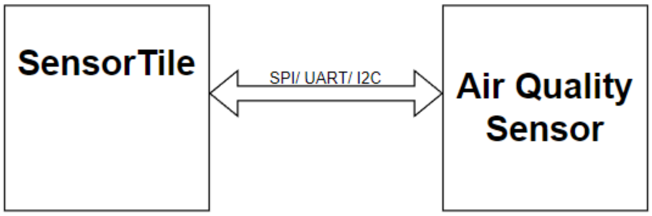

Figure 19: Depiction of connection of SensorTile and Air Quality sensors using an I2C/SPI/UART interface.

Figure 20: Depiction of connection of SensorTile to Air Quality sensors if not using a communication interface of SPI/I2C/UART

To monitor PM in the air the sensor SPS30 was selected, after its use in and heavy endorsement in [9] and recommendation in [2]. This also has the added benefit of having both an I2C and UART interface available, for this implementation the I2C interface will be used. To monitor gases in the air such as O3 and NO2 the MiCS-4514 was acquired in a breakout board SEN0377 made by DFRobot, this also employs the use of an I2C interface. Although it may have been more suitable to acquire a MQ135 device like in [10] [30] [31], which uses an Analog front end or a DGS-O3/DGS-NO2 like in [9], but availability issues at the time of need made these solutions unavailable.

For the power supply, if using the small cradle board, a battery connector and regulator to power the board is available, if deciding on using the larger cradle board an external 5V supply is needed to power the board and sensors. A previously designed board using an LDO (ADP7104, SOIC-8) that can have an input voltage range of 3.3V-20V and can output 5V if configured using a potentiometer [34].

D-II. Firmware Setup

STMicro provide a software package [17] to go along with the SensorTile board, this software package sets up the communication with the on-board sensors while also setting up the BLE communications via the Blue-NRG hardware. This software package makes data capture available through the GATT characteristics it has setup ,each characteristic is associated with a measurement. For the focus of this development, the motion characteristic was focused upon. When written (0100) to this characteristic (0x0012), the device reports the gathered accelerometer, gyroscope and magnetometer data [20]. The motion characteristic was altered to also transmit the environmental data gathered (temperature and pressure) as well as the air quality data gathered. The motion data acquisition and transmission is performed every 50ms, the environmental and air quality data acquisition and transmission is performed at a much slower rate (500ms or 5s).

Using the feedback provided during the data collection in Appendix E [24], to save power the SPS30 device is sent to sleep for 4s, woken up and have the data acquisition reported during the other second to report the PM data every 5s. This allows for relevant data collection of PM data to be gathered while also conserving power. After setup and initial reporting of data, the MiCS-4514 device was damaged and unusable, no replacement was ordered in its place.

D-III. Data Gathering Setup

From the insight provided in [21] and [20], a BeagleBone (BB) was setup with a Bluetooth adapter to use the Linux Bluetooth command line tools. To do this a C file was written to call the command recommended by [20] to obtain the motion data via the GATT Linux tool, while piping to a file name and terminating after a specified period. This made for an easy implementation of gathering raw data from the device.

D-IV. Data Interpretation

The data gathered was parsed using Python, this was done using the module binascii to unhexify the data captured and the int module to flip the Bytes correctly, as in the Bluetooth protocol the data is transmitted in a little-endian format. The data is then placed into a DataFrame and is plotted to optically display the changes in a feature over time. The Air Quality Index value is also calculated form the recorded values.

D-V. PCB Development

The PCB development was designed to house the purchased STMicro sensor tile, while incorporating aspects of the smaller cradle board into the design [16]. This design was implemented using KiCad v6. A power regulator (LDK130) to output the correct voltage supply for the device (3.3V), an additional power regulator (LDK130) to generate a 5V supply from the input supply to power the air quality sensors. A battery charging (STBC08) and fuel gauge (STC3115) IC [16], to monitor the charge in a battery along with controlling the charging mechanism to the battery when a power supply is present on a USB Micro terminal. There are also additional connectors for the SPS30 and MiCS-4514 (SEN0377) devices to connect to the I2C interface.

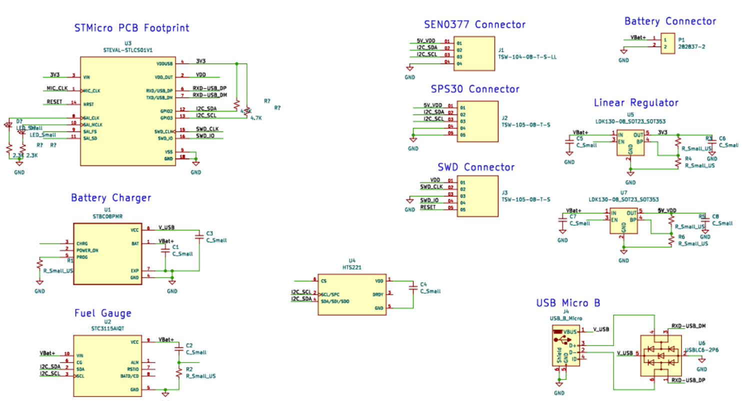

Figure 21: PCB Rev 1 Schematic

This PCB design is compact into a spacing of less than 27x40mm^2 (Figure 22), meaning the determining factor of space constraint in the X-Y directions is the SPS30 sensor

(41mmx41mm) [12]. The housing for this device can mocked in a box of size 60x45x30mm^3, A hollow shelf placed in the middle allows the SPS30 device to sit on the top half with the PCB placed on the bottom along with the battery supply while the MiCS-4514 device can be mounted using screw holes. This new housing designed would greatly reduce the space of the implemented design in Figure 23. The KiCad v6 files used in the design of this PCB are on the GitHub repository linked here, also uploaded to my DCU Google Drive here.

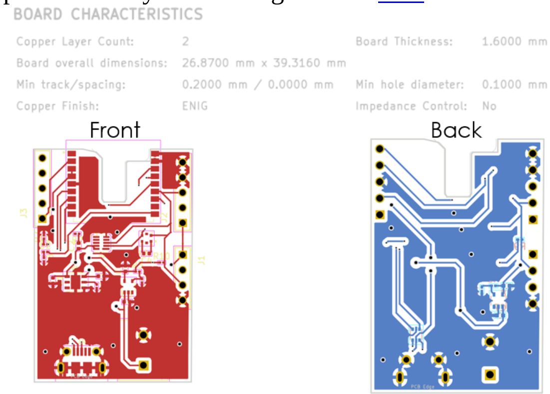

Figure 22: PCB layout top and bottom layers, also indicating the size of the PCB.

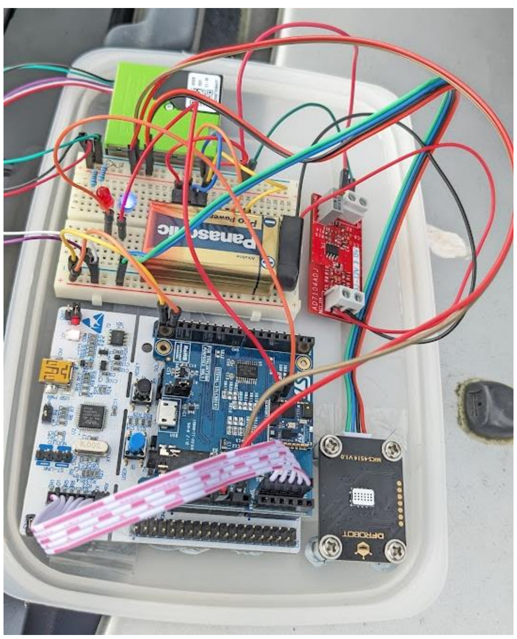

Figure 23: Implemented sample design.

Following the data collection and testing of the device it was discovered that the device being in motion did not exhibit a large effect on the device, this reduces the need for the additional motion sensors. Recommendation for a new PCB revision would include the following points:

- Remove the sensor tile board, use the same MCU and BLE devices (STM32L476jg and Blue-NRG)
- Can use a similar fuel gauge and battery charger.
- Can either use a similar linear regulator or opt to use a more efficient but noisier buck boost converter.
- Selection of a different sensor to monitor gas contents, like that in [9] (DGS-O3 or DGS-NO2).
- Keeping programming pins for the MCU and pins for connection to the SPS30 are essential to the development.

School of Electronic Engineering

Personalised Air Quality Monitor using Wearable Sensors

Appendix E
Testing & Results

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Appendix E

E-I. Testing Procedure

Testing the constructed device was done under differing conditions, these conditions were informed by the research performed. The approach in [6], where the researchers monitored data near a 24hr station reporting average data over an hour period [6] provided an insight into a re-creatable testing solution. As outlined in [6], this is a very useful method to calibrate the device when desiring to report data every hour. The reporting style from the known sources is very similar to that of the EPA [23].

Some papers investigated did not detail their testing procedures [7] [31], while others display the results of their tests without providing adequate conditions to the testing or providing reference measurements measured against [11] [10] [30]. While others like [6], provide detail around the measurements being performed to describe their experiments well, like that in [8] where experiments to validate the device designed is described along with experiments to test it in general use.

Using this information, it was decided that documenting the testing conditions was very important along with being able to provide a reference measurement to the device's result. To do this, it was decided to monitor the data nearby an existing EPA station [22] to have a reference to the result being produced. The reference data will provide feedback if the device is reporting data correctly. While recording the air quality data, this will be done under 2 further conditions:

A. While the device is stationary.
B. While the device is in motion.

These 2 further conditions will allow for understanding if the device being under motion may affect the measurements being performed. Measurements were planned for 2 EPA sites [22], Station 79 (Birr, Co. Offaly), and station 57 (Heuston station, Co. Dublin). The measurement setup is demonstrated through a video if desired to see how the data is collected, uploaded to my DCU Google Drive here.

E-II. Results

Measurements performed while nearby the Birr site was completed at approx. 100m away from the station, Figure 24. While initial measurements performed at the Heuston Station site was nearby, but weather dictated moving toward shelter due to the requirement of a laptop and the changeable weather, Figure 26.

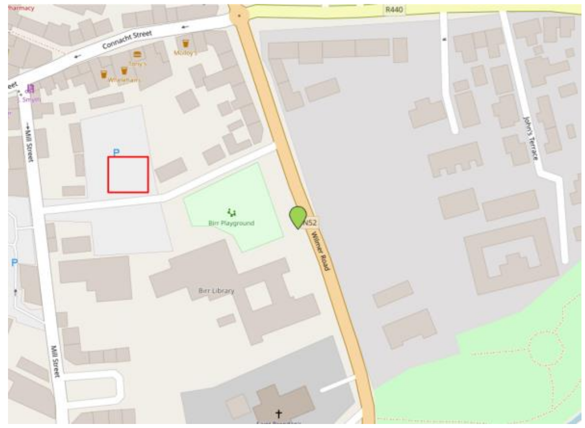

Figure 24: Green arrow represents location of the EPA station; the red box is the location where measurements are performed.

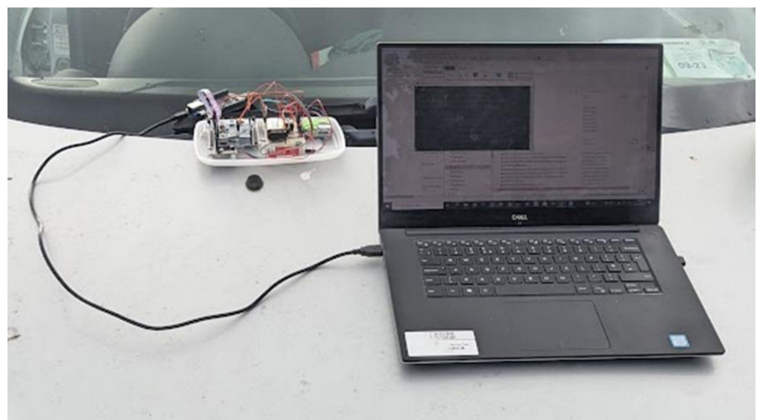

Figure 25: Measurement setup at Birr location

Figure 26: Green arrow represents location of the EPA station; the purple box shows the location of the initial measurements performed and the red box shows the location of the bulk of the data capture is performed.

Figure 27: Measurement setup at location of purple square in Heuston station

E-A. Raw Data Analysis

The resulting data capture from the Birr site, provided essential feedback showing a bug in the data capture code causing the data to be incorrect if an undesired condition was reached (Figure 28). Despite the errors encountered, some data collection proved to be useful, showing when data collected while stationary it is showing a result within the rated accuracy of the SPS30 device of 10µg/m^3 [12] (Figure 29), which is shown by the EPA data gathered at 18:00 - {10.7, 5.74} (Quoted as: {PM_{10}, $PM_{2.5}$} (µg/m^3)). During this data capture the high current consumption from the SPS30 device while in active measurement mode the entire measurement period was noticed as this drained the power supply. To move away from having the SPS30 device on all the time when performing measurements, the sample rate was decreased from once every 500ms to once every 5s, allowing for the SPS30 device to be sent to sleep mode for 4s and active for 1s.

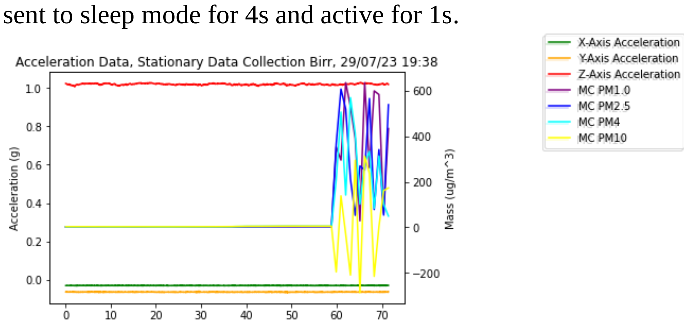

Figure 28: Data capture performed at Birr measurement site, PM and accelerometer data presented, showing an error being triggered in the code and incorrect data being captured.

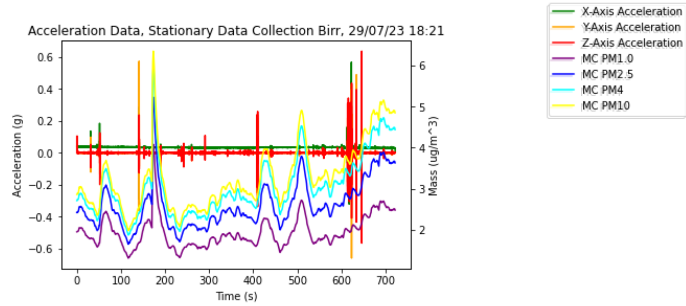

Figure 29: Data collection performed at measurement site while stationary, PM and accelerometer data presented, showing reasonable measurements gathered.

Before making this change in sample rate, data collection was performed at Heuston (purple site, Figure 26). This data is consistent (Figure 30) not showing a dependency on the temperature or pressure measured, although measuring less than data reported by the EPA station at the same time {4.77, 3.15}. After altering the sample rate to be decreased to 5s, there was an error in the coding setup which was noticed in incorrect data collection. After solving this issue data was collected at the Heuston site, red box (Figure 26). The data collected was slightly higher than the data gathered by the EPA station [22] {15.46, 9.08}, compared to the average over ~10-minute period being {16.32, 10.28}. The accuracy of 1µg/m^3 shown from this measurement is indicative of a well correlating measurement apparatus.

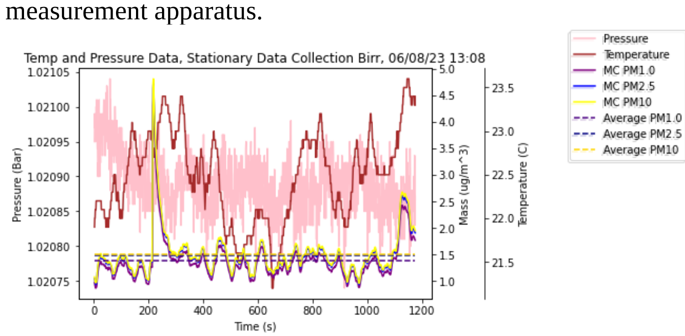

Figure 30: Temperature, Pressure plotted along with the PM data gathered at the Heuston (purple) site while stationary {1.52,1.49}

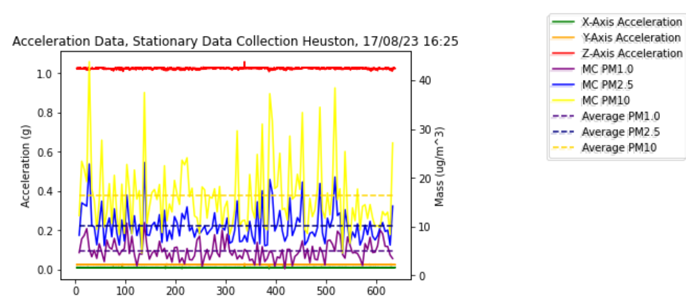

Figure 31: Stationary data collection showing accelerometer and PM data at Heuston (red) site.

E-B. Raw Data Manipulation

When operating correctly, the data captured clearly has a good correlation to the data captured by the EPA station. Although the data collection may not always go as smoothly as represented, to counteract this a 5-point moving average filter can be placed on the results being gathered. This will allow for the smoothing out of some errors experienced and not caught by a simple filter method (100µg/m^3 spike). Figure 32 showing the raw data gathered at the Birr site with an evident error in the readings spiking down to approx. -8µg/m^3, while Figure 33 shows the moving average filter put in place to attempt to get rid of such an event, which it successfully curtails the spike in error of measurement. As outlined in the Figure captions, the average of the entire data block does not change over this period correcting 1 error spike.

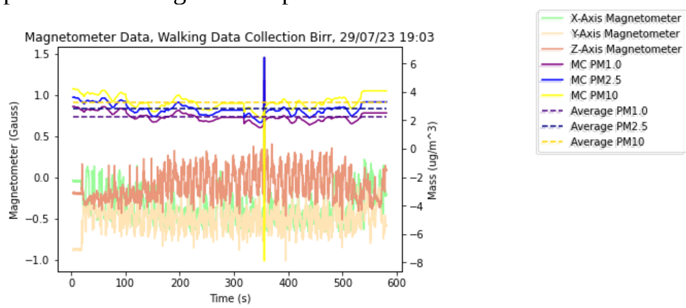

Figure 32: Magnetometer & PM data captured at Birr Site showing an average PM of {3.3,2.81}

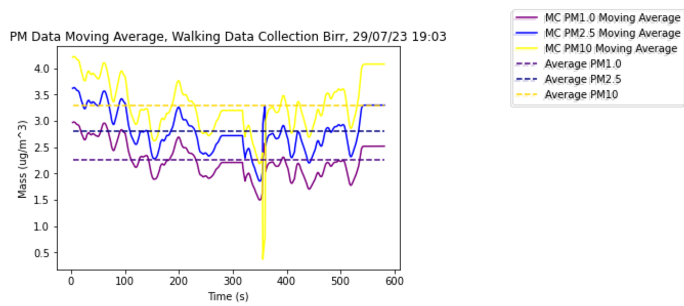

Figure 33: PM 5-point moving average of data gathered alongside average values of PM, showing average PM values of {3.3, 2.81}

The use of Air Quality Index Health (AQIH) as documented by the Irish EPA is outlined and discussed in Appendix A [4], in this discussion it is decided that representing data to a user would be best by calculating the AQIH as this is a reasonably easy to read scale for a user not familiar with the levels of PM in the air that is harmful to them [4]. In analysing the Raw Data, the AQIH is calculated every minute of data collection occurring, this is plotted against the Moving Average PM data in Figure 34 and Figure 35, in the stationary data produced, there appears to be no difference in calculating the AQIH values (The black dotted line overlaying the solid cyan line indicates this to be true). Whereas in Figure 35, there is a slight difference in the values calculated, this is indicated by the black dotted line not overlaying the solid cyan line. This is most likely due to the short period of calculating the AQIH values (1-minute windows). According to the AQIH scales [4], this is showing that the data gathered is indicating very good levels of Air Quality.

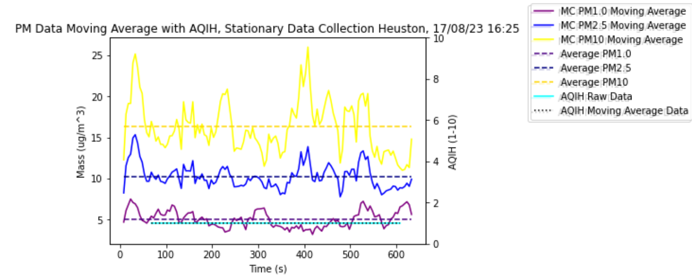

Figure 34: Moving Average PM Data plotted along with Average PM Data over the measurement period and AQIH which is calculated every minute, data collection performed while stationary.

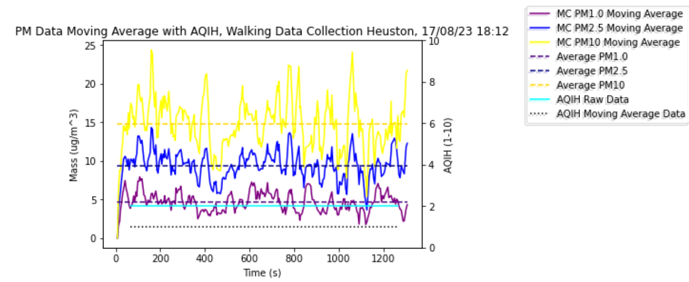

Figure 35: Moving Average PM Data plotted along with Average PM Data over the measurement period and AQIH which is calculated every minute, data collection performed while in motion.

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Appendix F
Source Code Listing

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Appendix F

There are numerous sets of code used throughout this project, from the programming of the MCU, retrieving the data and interpreting the data. This code is available for viewing on the Github repository linked here, also uploaded to my DCU Google drive here.

F I. Firmware Programming

As referenced in Appendix D [14], there was boiler plate code provided that allowed a start point for work to be completed [17]. This handles the setting up of the Bluetooth communications and the communications with the on-board sensors. This code was modified to setup the I2C driver and instantiate communications with the external Air Quality sensors (SPS30 [18] and MiCS-4514 [19]). Both drivers provided required modifications, without modifications to the SPS30 driver consistent errors in performing read and write operations occurred, the analysis of the SPS30 errors took significant time but was found and after inserting delays into the appropriate spaces these errors were no longer encountered. For the DFRobot_MICS driver provided [19], this was needed to be converted from a C++ implementation to a C implementation while also changing the method of reading and writing using an I2C bus to the specific methods used by the STM platform. The GATT motion characteristic (0x0012) was also altered so that when requested it will send the environmental data (Temp and Pressure) along with the Air Quality sensor data every 5s (Figure 36 and Figure 37). When sending the PM data the time stamp is set to FFFF, for the gas data it is set to EEEE and for the environmental data it is set to AAAA. This setting of the timestamp like so allows for ease of filtering to discern motion data from air quality or environmental data.

```c
    /* Motion Data */
    if(SendAccGyroMag) {
      SendAccGyroMag=0;
      SendMotionData();

      // Every 500ms enter loop
      if( env_count%_500MS_TIMER == 0 ){
          if( !aq_flag ){
              // Toggle LED every 500ms
              HAL_GPIO_TogglePin(GPIOG, GPIO_PIN_10);
          }
          else{
              // When SPS30 device is in active measurement mode keep GPIO on
              HAL_GPIO_WritePin(GPIOG, GPIO_PIN_10, GPIO_PIN_SET);
          }
      }
      // 4s elapse, wakeup SPS30 device and start measurements
      if( env_count%_4S_TIMER == 0 && env_count != 0 ){
          if ( !aq_flag ){
              ret = sps30_start_measurement();
              aq_flag = true;
          }
      }
      //5s elapse, read measurements from SPS30
      if( env_count%_5S_TIMER == 0 && env_count != 0 ){
        SendEnvironmentalData();
        readMOXData();

        if( aq_flag ){
            // Stop active measurements to lower current consumption
            sps30_stop_measurement();
            aq_flag = false;
        }
        env_count=0;
      }
      env_count++;
    }
```

Figure 36: Code inside the main loop that will read and send the motion, environmental and motion data (main.c).

Separate function was put in place to obtain the data from the SPS30 sensor and MiCS-4514 sensor while performing error checking to ensure the read and write operations to the devices were executed correctly.

```c
tBleStatus Air_Quality_Update(struct sps30_measurement* meas){
  tBleStatus ret;

  uint8_t buff[22];
  uint16_t tmp = (uint16_t)(meas->mc_1p0 * 100);
//  ALLMEMS1_PRINTF("Particles 1.0: %d\n", tmp);
  STORE_LE_16(buff   , 0xffff);
  STORE_LE_16(buff+2, tmp);
  tmp = (uint16_t)(meas->mc_2p5 * 100);
  STORE_LE_16(buff+4, tmp);
  tmp = (uint16_t)(meas->mc_4p0 * 100);
  STORE_LE_16(buff+6, tmp);
  tmp = (uint16_t)(meas->mc_10p0 * 100);
  STORE_LE_16(buff+8, tmp);
  tmp = (uint16_t)(meas->nc_0p5 * 100);
  STORE_LE_16(buff+10, tmp);
  tmp = (uint16_t)(meas->nc_1p0 * 100);
  STORE_LE_16(buff+12, tmp);
  tmp = (uint16_t)(meas->nc_2p5 * 100);
  STORE_LE_16(buff+14, tmp);
  tmp = (uint16_t)(meas->nc_4p0  *100);
  STORE_LE_16(buff+16, tmp);
  tmp = (uint16_t)(meas->nc_10p0 * 100);
  STORE_LE_16(buff+18, tmp);

  // Send the data to the Motion sensor characteristic handle
  ret = ACI_GATT_UPDATE_CHAR_VALUE(HWServW2STHandle, AccGyroMagCharHandle, 0, 22, buff);

  // Reset measured SPS30 values
  meas->mc_1p0 = 0;
  meas->mc_2p5 = 0;
  meas->mc_4p0 = 0;
  meas->mc_10p0 = 0;
  meas->nc_0p5 = 0;
  meas->nc_1p0 = 0;
  meas->nc_2p5 = 0;
  meas->nc_4p0 = 0;
  meas->nc_10p0 = 0;
  meas->typical_particle_size = 0;

  if (ret != BLE_STATUS_SUCCESS){
    if(W2ST_CHECK_CONNECTION(W2ST_CONNECT_STD_ERR)){
      BytesToWrite =sprintf((char *)BufferToWrite, "Error Updating Air Quality Char\r\n");
      Stderr_Update(BufferToWrite,BytesToWrite);
    } else {
      ALLMEMS1_PRINTF("Error Updating Air Quality Char\r\n");
    }
    return BLE_STATUS_ERROR;
  }

  return BLE_STATUS_SUCCESS;
}
```

Figure 37: Function written to send the Air Quality data to the Motion characteristic handle (sensor_service.c).

F II. Data Retrieval

As mentioned in the main paper and in Appendix D [14], a UCLA tutorial available online shows how to use a Beaglebone (BB) to interact with this device and request the relevant data [20]. Using this guide along with the relevant information from [21], the BB was setup and paired with the device to allow for connection and writing to the GATT characteristics. This was written into a bash script (data_collection.sh), which is further used in a C file (gatt_tool_use.c) to call the command sending the data to the specified file's name entered at run time, as well as setup a timer defined at run time to collect the data and kill the process. To be used as shown in Figure 38.

```
debian@beaglebone:~/masters_project_data$ ./data_collection_c.o filename.txt 60
```

Figure 38: Command line running compiled C program to retrieve data save to filename.txt and kill processes after 60s.

The command in the data_collection.sh file can be run directly in the terminal, this avoids an issue brought forward through the use of the compiled C file, which is the SensorTile device is locked, and the resource is unattainable requiring the SensorTile to be flashed again to be used.

F III. Data Interpretation

To interpret the data acquired, a Python class was written to parse the raw hexadecimal data recorded into lists, a Pandas DataFrame and save as csv file while also providing options to calculate the AQIH values given the raw data, calculate the 5-point moving average of the supplied data or plot the data to visualise said data. The 5-point moving average can be incorporated in the firmware using an array of length 5 units and continuously pushing and popping elements of the array, similar to a vector in C++. Likewise, the AQIH calculation exhibited can be replicated in the firmware development.

The main function shows the instantiating of the class and how best to use it. This is all in the file motion_data_parse.py available for viewing through the GitHub link provided.

```python
    '''
        Parsing the raw Motion Data into a set of lists for each variable
        Motion data is in hexadecimal little endian format
    '''
    def parse_motion_data(self, row, time_start):
        self.time_start_motion = row[36:42]
        self.time_start_motion = self.time_start_motion.replace(" ", "")
        self.time_start_motion = binascii.unhexlify(self.time_start_motion)
        self.time_start_motion = int.from_bytes(self.time_start_motion, byteorder=sys.byteorder)
        self.time_start_motion = time_start

        acc_x = row[42:48]
        acc_x = acc_x.replace(" ", "")
        acc_x = binascii.unhexlify(acc_x)
        acc_x = int.from_bytes(acc_x, byteorder=sys.byteorder)
        acc_x = self.twos_complement(acc_x)/1000
```

Figure 39: Depiction of Python file parsing the motion data using the binary to ascii library and a 2's complement function written.

```python
    '''
        Parsing the raw Environmental Data into a set of lists for each variable
    '''
    def parse_env_data(self, row):
        pressure = row[42:54]
        pressure = pressure.replace(" ", "")
        pressure = binascii.unhexlify(pressure)
        pressure = int.from_bytes(pressure, byteorder=sys.byteorder)
        pressure = pressure/100000

        temp = row[54:60]
        temp = temp.replace(" ", "")
        temp = binascii.unhexlify(temp)
        temp = int.from_bytes(temp, byteorder=sys.byteorder)
        temp = temp/10

        new_row = [self.time_start_motion, pressure, temp]
        # print(new_row)
        self.env_list.append(new_row)
```

Figure 40: Calculating the pressure and temperature data from the raw data collected.

```python
    '''
        Parsing the raw AQ Data into a set of lists for each variable
    '''
    def parse_aq_data(self, row):

        p1 = row[42:48]
        p1 = p1.replace(" ", "")
        p1 = binascii.unhexlify(p1)
        p1 = int.from_bytes(p1, byteorder=sys.byteorder)
        p1 = p1/100
        if self.prev > 0:
            if abs(p1 - self.aq_list[-1][1]) > 100:
                p1 = self.aq_list[-1][1]
```

Figure 41: Example of parsing the Air Quality data gathered

```python
    '''
        Converting the lists of converted data imported through the txt file into
        a DataFrame, for ease of use
    '''
    def convert_lists_to_df(self):
        self.aq_df = pd.DataFrame(self.aq_list, columns=['Time', 'Mass Concentration PM1.0',
                        'Mass Concentration PM2.5',  'Mass Concentration PM4', 'Mass Concentration PM10',
                         'Number Concentration PM0.5', 'Number Concentration PM1', 'Number Concentration PM2.5',
                         'Number Concentration PM4', 'Number Concentration PM10'])
        # Adding the moving average (Using 5 points to clalculate the moving average) column to df
        self.aq_df['Mass Concentration PM1.0 Moving Average'] = self.aq_df['Mass Concentration PM1.0'].rolling(window=5, min_periods=1).mean()
        self.aq_df['Mass Concentration PM2.5 Moving Average'] = self.aq_df['Mass Concentration PM2.5'].rolling(window=5, min_periods=1).mean()
        self.aq_df['Mass Concentration PM10 Moving Average'] = self.aq_df['Mass Concentration PM10'].rolling(window=5, min_periods=1).mean()
```

Figure 42: Calculation of the 5-point moving average

```python
        pm10_list = self.aq_df['Mass Concentration PM10']
        pm25_list = self.aq_df['Mass Concentration PM2.5']
        pm10_ma_list = self.aq_df['Mass Concentration PM10 Moving Average']
        pm25_ma_list = self.aq_df['Mass Concentration PM2.5 Moving Average']
        loc_time = self.aq_df['Time']

        for i in range(len(pm10_list)):
            if i%12 == 0 and i!=0:
                pm25 = pm25_list[-12:].mean()
                pm10 = pm10_list[-12:].mean()
                pm25ma = pm25_ma_list[-12:].mean()
                pm10ma = pm10_ma_list[-12:].mean()
                self.aqi_list.append(self.calculate_aqih(pm25, pm10))
                self.aqi_ma_list.append(self.calculate_aqih(pm25ma, pm10ma))
                self.time_aqi.append(round(loc_time[i], 3))
```

Figure 43: Filtering and calculating the AQIH values from the previous minute of results provided