AIR QUALITY MONITOR

by

Thomas Price

Bachelor of Technology in Electronics

Electrical and Computer Engineering Technology

British Columbia Institute of Technology

April 2017

AIR QUALITY MONITOR

by

Thomas Price

DiplT British Columbia Institute of Technology, 2007

AN INDUSTRY PROJECT REPORT SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF TECHNOLOGY IN ELECTRONICS

Electrical and Computer Engineering Technology

We accept this report as conforming to the required standard

…………………………………………

…………………………………………

…………………………………………

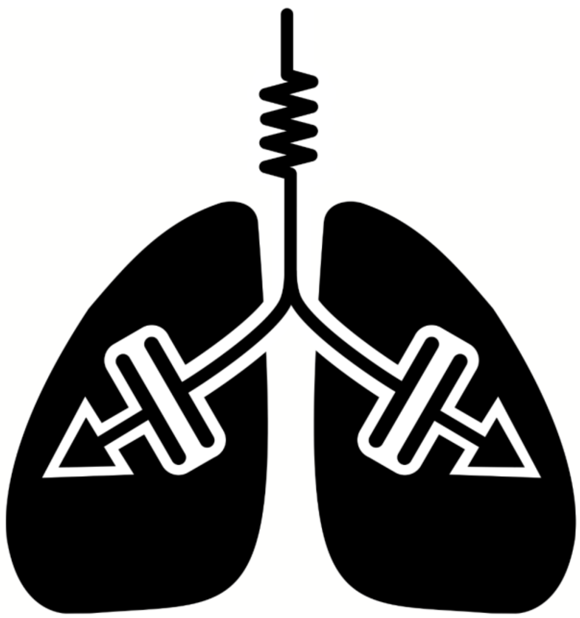
…………………………………………

British Columbia Institute of Technology

April 2017

ABSTRACT

The quality of air you breathe is an important but often ignored aspect of the workplace. Recent research has shown that air quality can have a drastic impact on factors of long term health. As our society ages, health problems induced by poor air quality tax the healthcare system. A low-cost device is not available for monitoring home or workplace air quality. With a number of recent cost reductions in areas such as micro-electro-mechanical systems (MEMs) and internet of things (IoT) providing easy internet access, it is now possible to create such a device. This included design acts as a reference platform as well as a tool to measure common environments and possible changes we can make. The hope is that this low-cost device can be monitored in a distributed fashion throughout our workplaces, creating greater awareness of air quality and its importance.



1 Table of Contents

1 INTRODUCTION

1.1 Brief Introduction

In my work environment, we deal with dust, solvents and other cleaning materials. While speculating about what is safe or not and best practices, I didn’t have any hard evidence. This lead to the discovery of low cost heated gas sensors. The sensor series start with “MQ” and follow with a number to identify what gas they are sensitive to. For example, MQ-5 will detect natural gas, coal gas, and MQ-6 will detect propane levels. After purchasing a few and researching further, I discovered a number of previously expensive air monitoring sensors are now available at low cost. While some consumer air quality units are currently available, they use broad range sensors that cover a range of gasses, without narrowing down specific problem areas. Additionally, with consumer smoke or carbon monoxide alarms, there is a single alarm level and no visible numerical reading.

My desire was to integrate several common sensors, important to air quality, into a compact standalone product to perform sampling in my work environment. This would allow me to analyze recorded data and apply filtering or other changes to the environment and observe the effect. It would also allow alerting me if hazardous conditions are present, to reduce my exposure and effects upon my health.

I have worked with embedded microcontrollers in the past for projects such as motor and temperature controllers. Using PIC and AVR microcontrollers and their development environments. In this case I wanted to learn an additional platform to expand my knowledge.

2 EXISTING WORK

2.1 Existing products

2.1.1 Air Quality Egg

Fig. 2.1. The Air Quality Egg

Air quality egg is a crowd sponsored air quality monitor from 2012. It is designed to measure several aspects: nitrogen dioxide (NO_2), carbon monoxide (CO), temperature and humidity. It is also expandable if other inter-integrated circuit (I^2C) sensors need to be added.

The sensor is networked and data is intended to be shared to form a community driven monitoring of air quality [CHAN13]. A map on their site allows viewing of all the online eggs to see air quality in some area. This is a great idea and ideally could be integrated into this product, or the system could be adapted to appear as an air quality egg.

Sensors used: E2V MiCS-5525 heated CO, and MiCS-2710 heated NO_2, and DHT-22 for temperature/humidity. O_3, SO_2, and particulate models are also available, but are not integrated into a single unit. Carbon monoxide and NO_2 are given in parts per billion (ppb) values, typical readings from the device are from 1,100 to 15,000 ppb.

Sensors do not come calibrated, and I wanted to avoid the cost and complexity of calibrating heated sensors in this project. I would not be comfortable relying on using uncalibrated sensor data to report air quality health aspects to a user.

The cost of the egg is $280, which is a good target budget for my device. It is in the range of a consumer purchase, but not too low to sacrifice by using lower cost and accuracy sensors.

2.1.2 Xiaomi PM2.5 Sensor

Fig. 2.2. Xiaomi's particulate sensor

Xiaomi Mi PM2.5 sensor is a compact and portable particulate matter sensor, with integrated fan and rechargeable battery [GEAR16]. Xiaomi is a Chinese company, and China is widely reported as having air quality issues, particularly with particulate matter. So, it can be seen why this low cost single use design was brought to the market. It is available for under $120. The Mi is an example of modern consumer design, and would be something to strive for in a finished product.

Criticism

Limited sensors, for Xiaomi to add temperature and humidity monitoring is very inexpensive (less than $2). However, other sensing such as CO, CO_2, etc. comes at a significant cost, so it is understandable why they would not integrate these. Limited availability of accuracy from Xiaomi, I could not find specifications on sensor accuracy or airflow.

2.2 Literature Search

The following terms were used to search for existing literature: "air quality monitoring device", "indoor air quality measurement". A few relevant articles were found and are discussed here.

Additionally, literature on effects of numerous gases on human health (CO, CO_2, etc.) was searched and is referenced in the relevant sections (see section 3, AIR QUALITY ASPECTS).

2.2.1 Electronic nose based on solid state sensor arrays for low-cost indoor air quality monitoring

S. Zampolli et al focus on monitoring indoor air quality for appropriate ventilation, ensuring safe and comfortable living conditions [ZAMP04]. They identify building-related illnesses (BRI) as well as sick building syndromes (SBS), and highlight the shortcomings of existing HVAC systems. Specifically, HVAC will generally operate at fixed duty cycles, which will not respond to changes in air quality and may be relying on less than ideal outdoor air.

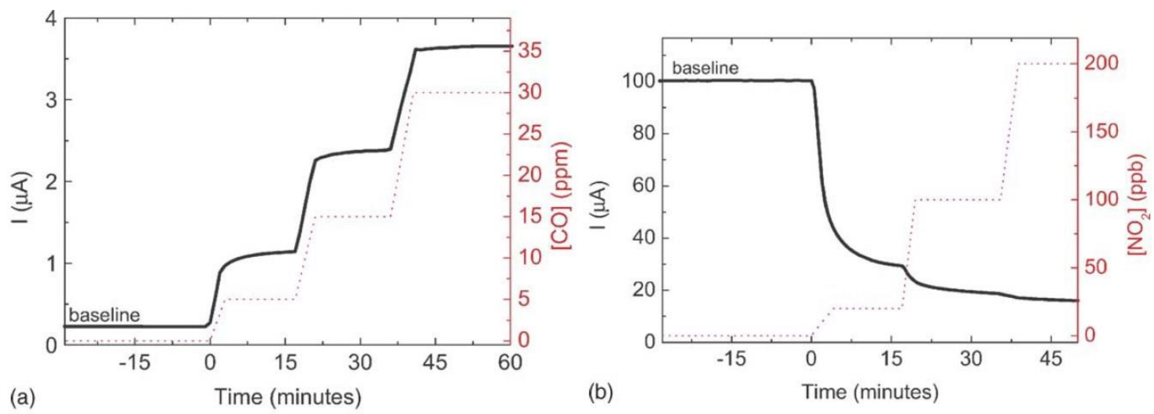


Fig. 2.3. Current measurements from the heated CO and NO_2 sensors used in the study

Zampolli's test device operated for 45 days and could identify levels down to 20 ppb for NO_2 and 5ppm for CO_2. Note in Fig. 2.3 the very low levels of current produced by the CO sensor in the areas of interest below 10ppm (tens of nanoamps). This highlights the difficulty in producing a low-level CO sensor for air quality purposes.

An interesting application they proposed is for the air monitoring device to be integrated into an HVAC system. With more connected devices being available, it would be realistic to use the AQM to communicate via WiFi to the home HVAC system. If CO_2 or particulate levels were seen to rise, additional ventilation would be activated, and the user could be reminded to change or clean their filter.

2.2.2 Urban air quality measurement, low-cost, high-density networks (University of Cambridge)

A number of University of Cambridge authors in addition to a gas sensor manufacturer (Alphasense Ltd.), collaborated to produce an air quality monitoring device for portable measurement [MEAD13]. One of their main goals was to produce a low-cost device while still maintaining good accuracy. Specifically, they were able to utilize ppm quality measurement sensors for ppb level monitoring.

Sensors used were CO-AF, NO2-A1 and NO-A1 for measuring CO, NO_2 and NO respectively. While the sensors were based on commercially available models, they had been modified to produce greater signal-to-noise ratios at these low measurement levels. Additionally, extensive calibration was performed using gas mixing and a zero air generator (important for determining zero point offsets).

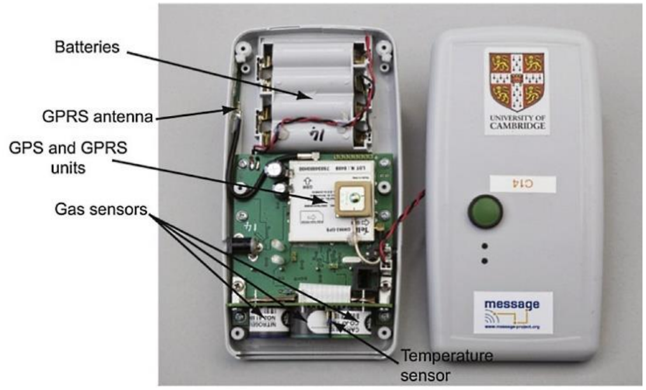


Fig. 2.4. Cambridge portable air quality monitor [MEAD13].

The Cambridge study is incredibly detailed and covers detailed aspects of sensor operation, calibration methods, and multiple field studies. For example, in Fig. 13 of their study, they were able to use their portable monitor to record air quality data (CO and NO_2). The volunteers walked along a set path and data was logged. The data was captured a few times to form a comparison, and then overlaid on the Google Maps image.

More information was obtained when comparing different commuting methods. They compared pedestrian, cycling, and vehicular travel. From Mead et al. results, we see in this case that cycling produced the lowest total exposure to CO, and vehicle travel the highest.

With requirements of portability comes compromise, however, and they are limited to measuring three aspects of air quality, all being hazardous gas levels. Ultimately, with my design the same compromise must be made. I chose a different selection of air quality measurements, but to say one or the other is more important is short-sighted. We must be observant of all aspects of air quality in our society.

3 AIR QUALITY ASPECTS

There are many aspects to air quality, hazardous gases may be present in the air you breathe causing sickness. Small particles as well as mold spores may be suspended in the air, and after entering the lungs could cause irritation or inflammation. A few of these aspects were discussed below, and an even lower number were chosen to be integrated into the air quality monitor (AQM).

3.1 Particulate Matter

Particulate matter is present in abundance in the modern environment, and is recently being acknowledged as a major factor for health. In urban areas, greater access to technology extends life, but the emissions from this tech (automobiles, factories) counteracts this.

Particles are measured in reference to their size, PM10 refers to particles with a median diameter of 10µm. PM2.5 particles have a median diameter of 2.5µm [DIAM10]. These are believed to cause the greatest risk to health, as the tiny particles will lodge deep into the lungs. Source of fine particulate matter (0 - 2.5µm) can originate from combustion. In an electrical environment, this can occur during soldering. If care is not taken to select appropriate temperatures and adequate fume extraction is not present, particulate matter will be generated and easily enter the lungs.

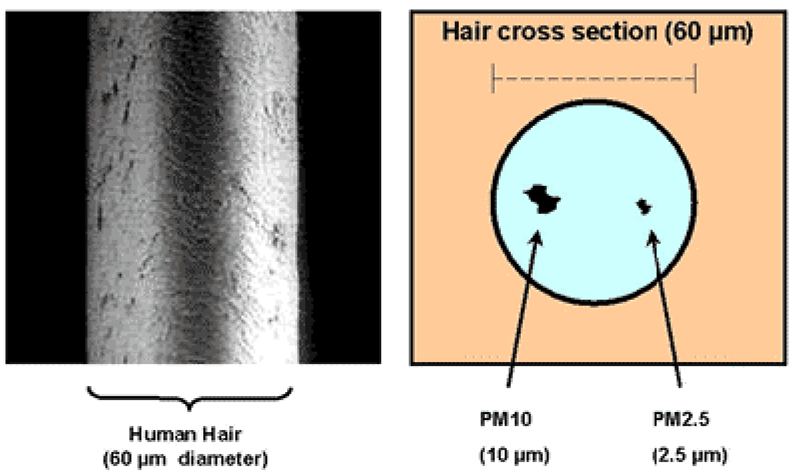


Fig. 3.1. Size comparison of particulate matter types [SMIT17].

A study in Hong Kong found that for every 10 micrograms per cubic meter (µg/m³) increase in PM2.5 exposure, elderly saw a 22 percent increase risk in dying of cancer [WONG16].

Coarser particulate matter (2.5-10µm) can originate from grinding operations or dust from roads. Coarse matter is less likely to originate in an electronics workplace. However, it is possible when maintenance is performed on a dirty product, these particles could come loose and enter the air (such as in an electronics repair facility).

PM2.5 has been shown to increase the risk of coronary events, and hardening of the arteries, known as atherosclerosis [CESA14].

3.1.1 Particulate Levels

There is no minimum recommended exposure level of PM2.5, all levels are dangerous. However, we must have some accepted level of harm, based on current science. The World Health Organization (WHO) guidelines state that cities with average annual PM2.5 exposure of 12µg/m^3 and 15µg/m^3 had significant increases in risk of health. Below that the uncertainty in risk widens, and is assumed to be safe at this time. Several other countries have set guidelines for reasonable exposure limits as well, and are listed below.

Country	Agency	Daily average	Annual average
	WHO	25µg/m^3	10µg/m^3
Australia	NEPC	25µg/m^3	8µg/m^3
Canada	CCME	30µg/m^3	-
USA	EPA	35µg/m^3	12µg/m^3

Table 3.1: PM2.5 particulate matter exposure limits

Country	Agency	Daily average	Annual average
	WHO	50µg/m^3	20µg/m^3
Australia	NEPC	50µg/m^3	-
Canada	CCME	No set limit	-
USA	EPA	150µg/m^3	-

Table 3.2. PM10 particulate matter exposure limits

Overall, we can see a level of agreement of around 25-30µg/m^3 for daily average (24hr) and 10µg/m^3 for the year.

Note that for Canadian CCME, while PM10 does not have a guideline for an upper limit, it is stated that PM10 will generally follow PM2.5 [CCME00]. Therefore, if PM2.5 levels are kept within the 30µg guideline, we can expect PM10 levels to be reasonably low as well. The WHO guidelines also reinforce this by referencing a PM2.5/PM10 ratio of 0.5 to 0.8 for developed country urban areas [WHO06].

For the US, the daily average PM10 level limit is quite high at 150µg/m^3, with the requirement that this level should not be exceeded more than once per year. This highlights the importance of low-cost continuous monitoring. Having an air quality sample performed one or two times per year could miss serious violations of the limit.

3.1.2 Hazardous Particulate Matter

What is discussed so far is simply a count of the suspended particulate matter present in the air. Whether the particles are innocuous or inherently hazardous has not been determined. There are many cases where certain materials will have a more harmful effect on the body. For example, inhalation of silica dust can cause cough, fatigue, fever and potentially death. It is classified as one of the most harmful components of particulate matter [EWG14].

Other examples exist, such as lead and asbestos, which are fortunately on the decline. In these areas, low-cost methods of determining the composition of PM is not possible. We must simply measure the level and make judgements based off that, assuming the composition of particulates is typical.

To do proper measurements, air sampling and performing lab analysis on the captured particulates is necessary. The lab can then check for high-risk compounds or biological levels for things such as mold spores.

This does not mean low cost monitoring of PM is useless, it is still extremely useful for detecting elevated particulate levels, which could flag future lab analysis and investigation.

3.1.3 Particulate Matter Conclusions

Ideal level:

- Ideal workplace concentration of PM2.5 is less than 10μg/m^3.

Alert level:

- Above 30μg/m^3 for 24 hours to signal user to increase ventilation, and investigate HVAC filtration or possibly implement new filters.

Alarm level:

- Above 200μg/m^3 for 5 minutes to signal concerning levels of PM are present, user should stop activity and process should be investigated.

3.2 Gases

3.2.1 Oxygen (O_2)

Oxygen is critical to human respiration and constitutes 21% of the earth's atmosphere.

Oxygen can be toxic at high levels (50%) where visual distortions, bleeding, seizures, and shortness of breath are seen. Low levels (19% or less) are also harmful and fainting is imminent at 10% or less.

Oxygen concentration (% vol)	Health effects of persons at rest
19	Some adverse physiological effects occur, but they may not be noticeable.
15–19	Impaired thinking and attention. Increased pulse and breathing rate. Reduced coordination. Decreased ability to work strenuously. Reduced physical and intellectual performance without awareness.
12–15	Poor judgment. Faulty coordination. Abnormal fatigue upon exertion. Emotional upset.
10–12	Very poor judgment and coordination. Impaired respiration that may cause permanent heart damage. Possibility of fainting within a few minutes without warning. Nausea and vomiting.
<10	Inability to move. Fainting almost immediate. Loss of consciousness. Convulsions. Death.

Table 3.3 Health effects of reduced atmospheric oxygen [APAC04].

Exposure to high levels of oxygen is not common. Low levels are more common as it is consumed by combustion, so an inadequately ventilated gas stove could cause levels to plummet (among other things). Humans do consume oxygen as well of course:

"The air that is inhaled is about 20-percent oxygen, and the air that is exhaled is about 15-percent oxygen, so about 5-percent of the volume of air is consumed in each breath and converted to carbon dioxide. Therefore, a human being uses about 550 liters of pure oxygen (0.55 m^3) per day."

If we consider an average office to be 17 m^3, 0.023 m^3 of oxygen is consumed every hour. In a sealed office, this would lower the level from 21% to 20.9%. The Canada Occupational Health and Safety regulations list an oxygen deficient atmosphere as 18% and the US OSHA defines it much higher at 19.5% [MCMA09].

It is difficult to find references to indoor air quality measurements with oxygen sensors. It's not clear if it is just not an issue in general, or if it is due to the greater difficulty and higher cost to measure oxygen at reasonable resolutions.

Either way, due to high cost of oxygen sensors and difficulty of calibration (see section 4.1.2.2 Available Sensors), it will not be an aspect measured in this AQM.

3.2.2 Carbon Dioxide (CO_2)

Carbon dioxide (CO_2) is an odorless, colorless gas. It is produced naturally through decomposition and respiration, and in industry through activities such as burning fossil fuels for electricity and transportation. Carbon dioxide is re-absorbed by plants and micro-organisms (the carbon cycle). Carbon dioxide currently forms 0.04% of the earth's atmosphere [UCAR06].

3.2.2.1 Safety levels

At high concentrations (5-10%), CO_2 will have a sharp acidic odor. However, safety issues occur far below this level and may be difficult to determine the cause as being CO_2. Below is a diagram highlighting the percent CO_2 and negative effect on various areas of the body (1% = 10,000 ppm).

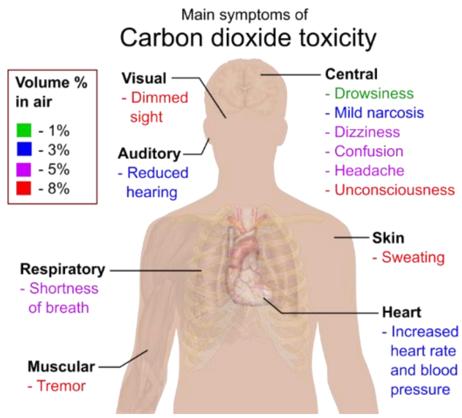


Fig. 3.2. Effects of CO_2 at various levels [HÄGG14]

At concentrations of 1%, slight increase in breathing is present. 2% concentration causes breathing rate to increase 50% above normal. At concentrations of 2-10%: nausea, dizziness, headache, mental confusion, increased blood pressure and respiratory rate. Above 8%: nausea and vomiting. Above 10%: death. Exposure of CO_2 at these extreme levels for long periods of time can have permanent effects on health. Damaging retinal ganglion cells (can affect vision), cerebro-retinal degeneration [SEVE67], and central nervous system may occur.

3.2.2.2 Workplace sources of CO_2

Natural breathing

Sources of CO_2 include natural breathing from employees. When air is inhaled, it will contain approximately 0.04% CO_2 and 5% when exhaled (400 ppm and 50,000 ppm respectively). If a room is fully sealed, this CO_2 level will continue to increase until breathing stops.

Combustion

An example of combustion is a chemistry labs Bunsen burner. When burning a single gallon of propane fuel, 12.7lb of CO_2 is produced [EIA16]. Additionally, this process consumes oxygen, another route of potential risk (see 3.2.1 Oxygen).

Dry ice

Dry ice is the solid form of CO_2, occurring at temperatures of below -56.6 °C temp (sea level). Dry ice is used in the beverage industry to produce carbonation, in shipping to keep items cool, welding, and numerous food processing applications. If a 1kg block of dry ice was placed in a small sized room (2x2x2m) with no circulation, the CO_2 concentration would raise from 0.04% to approximately 6%:

1kg CO_2 x (1mol CO_2 / 44g CO_2) x 1000g = 22.7 mol CO_2

2x2x2 = 8m3 = 357 mol * 0.04% CO_2 = 0.14 mol CO_2

22.7 mol + 0.14 mol = 22.8 mol

22.8 mol / 357 mol = 6.4%

The resultant level of CO_2 would cause confusion and headache. 2kg of dry ice in the same room would lead to death. With adequate air circulation, this would not produce any problems. This shows the importance of installing and maintaining a circulating air HVAC system in industrial environments.

3.2.2.3 Health issues at low levels

At rates within normal ranges (350 - 2,500 ppm) CO_2 is not believed to be a cause of negative health effects. However, studies have found associations between CO_2 and numerous negative health reports, collectively referred to as sick building syndrome (SBS) [LU15]. The top reported symptoms include eye dryness, dizziness, tiredness, and difficulty concentrating. Sick building syndrome was correlative with higher concentrations of CO_2 (above 800 ppm), which often relates to lower building ventilation [SEPP99]. Symptoms decreased continually with CO_2 levels below 800 ppm and reached a levelling off point at 500 - 600 ppm, ideally a workplace environment would be within a normal range of 400 - 600 ppm. While lower concentrations of CO_2 could also pose a risk to health, the possibility of this is much lower than excess CO_2. Ideally the measurement system would be able to flag "too low" CO_2, however this will not be a requirement of the chosen CO_2 measurement sensor.

A Berkeley study looked at decision-making performance, and found that even at low levels of CO_2 (1,000 ppm), performance is reduced in many areas. At a higher tested level of 2,500 ppm, subjects were rated as dysfunctional and task performance decreased dramatically.

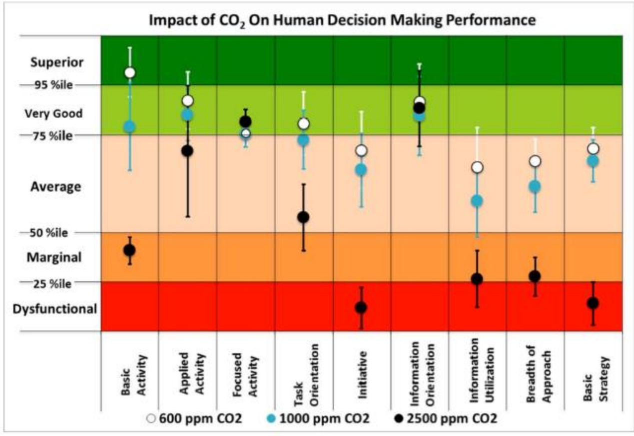


Fig. 3.3. Impact of CO_2 on human decision making [SATI12].

3.2.2.4 Measuring methods

Measuring CO_2 requires a few considerations to achieve useful data:

- Use steady state CO_2 not peak
- Do not measure air directly exhaled as these levels will be higher than the average of the room
- Do not place sensor near air intakes, exhausts, open windows, or doors
- Place sensor at the height of inhalation (approx. 125cm for seated male).

Be aware that that CO_2 is heavier than air, so it is possible to accumulate in low lying areas.

3.2.2.5 Mitigation methods

Available methods to mitigate high carbon dioxide levels are:

Green plants

Plants naturally consume carbon dioxide and emit oxygen during a process known as photosynthesis. The carbon is converted into sugars which feed the plant, and water supplied to the plant becomes the oxygen we breathe.

In addition to reducing carbon dioxide, plants are effective at filtering the air from other compounds. Reductions of 50-75% of VOC's were found when an office (50 m^3) had only three plants added. In addition to the foliage, potted plants contain a number of microbes in the soil that the study found were performing some filtering. With just the soil however, the filtering would not last forever, it is necessary for the plant and soil to be present to form a complete system [WOOD06].

The cost of a handful of table sized potted plants used in the studies is minimal, they can be found for $20 each. Maintenance cost is also very low, although maintenance is required often (watering every few days).

Plant species

Peace lily has been used by NASA as well as the previously referenced office study for reducing VOCs and carbon dioxide. It is capable of removing benzene, formaldehyde, trichloroethylene, xylene, and ammonia.

When comparing plants based on carbon dioxide reduction, we can use photosynthetic efficiency as a benchmark. Photosynthetic efficiency is the portion of light energy converted to chemical energy via photosynthesis. A typical plant can be anywhere from 0.1 to 2%, with crop plants generally being higher [GOVI16].

Since the Ronald A. Wood study concluded that no change in carbon dioxide was seen [WOOD06], it is not realistic to pick an ideal plant based on efficiency. Additionally, even if a crop plant were capable of significantly reducing levels (e.g. sugarcane), it is not realistic to have space for such plants in an office environment.

Cycling air

Cycling air is the simplest method of reducing CO_2 levels and has near infinite capacity. Opening a window will ensure air is exchanged with the outside, keeping CO_2 from reaching dangerous levels. A major downside is when weather conditions are not comfortable, on a cold day, hot air will escape outside, causing the heating system to work overtime. It’s possible to mostly mitigate these losses by using a heat exchanger, this is known as heat recovery ventilation (HRV). Warm air from inside is passed through a heat exchanger and then is exhausted outside. Fresh air from outside enters the same heat exchanger and is heated before entering the building. Typical air to air heat exchangers are from 50-70% efficient (e.g. Venmar EVO5-700 HRV).

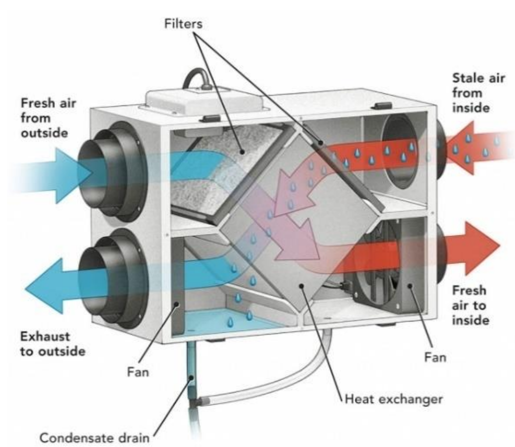


Fig. 3.4 Diagram of a household heat recovery ventilator.

CO_2 scrubbing

It is possible to scrub the air inside an office without pulling outside air, that would require heating or cooling. Some methods include activated carbon, regenerative removal systems, and a few mineral based options. For carbon, air is passed through a bed of activated carbon, micropores in the carbon trap and hold onto CO_2 molecules (spheres have been demonstrated to hold 8.1 mmol/g). Once the medium is saturated, low CO_2 air is blown through the bed to free the trapped CO_2. Mineral removal involves reacting CO_2 with minerals (Mg or Ca) to form stable carbonates. To sequestrate 1kg of CO_2 would require the use of 3kg of magnesium silicate mineral.

3.2.2.6 CO_2 conclusions

Ideal level:

- Ideal workplace concentration is 400 – 600 ppm to provide best health and performance of users.

Alert level:

- Above 2,000 ppm to signal user to increase ventilation, open a window or door.

Alarm level:

- Above 5,000 ppm to signal dangerous levels of CO_2 are present, user should find fresh air and then investigate reason for alarm.

3.2.3 Carbon Monoxide (CO)

Carbon monoxide is an odorless colorless gas that can cause illness and death. CO is produced when burning fuel (oil, coal, wood, or gasoline) as well as incomplete combustion (such as smoking a cigarette). Low levels of CO will cause flu-like symptoms: tiredness, headaches, and weakness. High levels or long term exposure will cause dizziness, chest pain, vision issues, and difficulty thinking. Very high levels result in coma and death.

3.2.3.1 Safety Levels

CO CONCENTRATION IN AIR	INHALATION TIME AND SYMPTOMS
9 ppm	ASHRAE maximum allowable concentration for short exposure in a living area.
50 ppm	Maximum allowable concentration for continuous exposure in any 8-hour period.
200 ppm	Headache, tiredness, dizziness and nausea after 2 to 3 hours.
400 ppm	Frontal headache within 1 to 2 hours and life threatening after 3 hours. Maximum allowable amount (air-free) in flue gases.
800 ppm	Dizziness, nausea and convulsions within 45 minutes. Unconsciousness within 2 hours. Death within 2 to 3 hours.
1,600 ppm	Headache, dizziness and nausea within 20 minutes. Death within 1 hour.
3,200 ppm	Headache, dizziness and nausea within 5 to 10 minutes. Death within 30 minutes.
6,400 ppm	Headache, dizziness and nausea within 1 to 2 minutes. Death within 10 to 15 minutes.
12,800 ppm	Death within 1 to 3 minutes.

Table 3.4 CO exposure levels and their symptoms.

The primary method of carbon monoxide (CO) toxicity is hypoxia. When inhaled, it is absorbed in the lungs and binds with hemoglobin at an affinity 234 times that of oxygen. This causes a greatly reduced level of oxygen in the blood (hypoxia). Additionally, CO reduces the oxygen release rate into the cells, a potent combination [TOWN02]. The table above highlights various CO ppm levels and their respective impacts on health.

3.2.3.2 Health issues at low levels

CO Level	Action
0.1 ppm	Natural atmosphere level or clean air.
1 ppm	An increase of 1 ppm in the maximum daily one-hour exposure is associated with a 0.96 percent increase in the risk of hospitalization from cardiovascular disease among people over the age of 65. (Circulation: Journal of the AHA, Sept, 2009)
3-7 ppm	6% increase in the rate of admission in hospitals of non-elderly for asthma. (L. Sheppard et al.,Epidemiology, Jan 1999)
5-6 ppm	Significant risk of low birth weight if exposed during last trimester - in a study of 125,573 pregnancies (Ritz & Yu, Environ. Health Perspectives, 1999).
9 ppm	EPA and WHO maximum outdoor air level, all ages, (TWA, 8 hrs). Maximum allowable indoor level (ASHRAE) Lowest CO level producing significant effects on cardiac function (ST-segment changes, angina) during exercise in subjects with coronary artery disease. (Allred et al., Environ. Health Persp., 1991). Most common indoor air level triggering action by local Authorities of Jurisdiction. (CAL, Penny)
10 ppm	Significant increase in heart disease deaths and hospital admissions for congestive heart failure (JAMA, Morris, Penny)
15-20 ppm	World Health Organization lists as causing impaired performance, decrease in exercise capability, shortened time to angina response and vigilance decrement.(WHO, 13)
20 ppm	Typical concentration in flue gases (chimney) of a properly operating furnace or water heater/boiler. (T.H, Greiner, ISU)
25 ppm	Chronic exposure during pregnancy to miniscule levels of carbon monoxide damages the cells of the fetal brain, resulting in permanent impairment. (UCLA Study, *BMC Neuroscience*, June 22, 2009)
27 ppm	21% increase in cardio-respiratory complaints. (Chest, Kurt et al , 1978)
30 ppm	Earliest onset of exercise induced angina (HbCO 4.96% - World Health Organization, 13)
35 ppm	Level which most fire department require that firefighters put on their oxygen masks. Maximum allowable outdoor concentration for one-hour period in any yr. (EPA, ASHRAE)
50 ppm	In healthy adults, CO becomes toxic when it reaches a level higher than 50 ppm.

Table 3.5 Low CO levels and their effects.

3.2.3.3 Household CO alarms

A typical home CO detector will meet UL standards (UL-2034) and should respond in the following times [BAIL17]:

CO concentration	Alarm time range
30 ppm	30 days
70 ppm	60 – 240 minutes
150 ppm	10 – 50 minutes
400 ppm	4 – 15 minutes

Table 3.6 Household CO detector response times.

While this is useful for safety and avoiding death, for air quality we care about much lower levels, as discussed above.

3.2.3.4 CO conclusions

Ideal level:

- Ideal workplace concentration is 2ppm or less for optimal health

Alert level:

- Above 8ppm to signal user to increase ventilation or investigate cause of CO production.

Alarm level:

- Above 50ppm to warn user to turn off any combustion equipment and ventilate as soon as possible.

3.2.4 Flammable gases

Many workplace solvents are chosen to evaporate quickly, convenient for cleaning but not good for air quality. If these volatile chemicals are not vented or filtered adequately they can build up and risk igniting or causing loss of consciousness. However, for air quality the concentrations of flammable gas are much lower, often not detectable by scent or difficulty of breath. The main concern is long term effects such as cancer or damage to lung tissue.

The design can have provision for mounting a specific flammable gas sensor, if the workplace deems appropriate. Designing an ignition safe product is not a simple task, so the equipment would be for monitoring low levels only.

3.3 Temperature

Ambient temperature can often be a personal preference in the workplace. In some conditions, temperature will reach extremes, for example working outdoors, near an oven, or around a freezer.

For workplace performance, the consensus is that 21-22°C is ideal and performance will decrease above about 23°C [SEPP06].

In terms of health, higher temperature is associated with increased risk to die from cardiovascular, respiratory, and cerebrovascular diseases. Certain groups are more vulnerable, elderly and infants, as well as those with lower socioeconomic status. In a Mediterranean study, a small 1°C increase of apparent temperature corresponded to a 3% increase in daily mortality. Korea saw an even greater effect of 7 to 16% across various cities.

At very high ambient temperatures and workloads, heat-related deaths have been reported. Recommendations from current studies are that: at 39°C ambient, no level of work is recommended. Heavy work can begin at 31°C if there is adequate rest (75% duty cycle). This temperature would also be suitable for continuous light work (office work).

Temperature can also interact with other effects, for example, PM10 will exhibit more adverse health effects on warm days than cool days [REN06]. Which can be another important trigger to the HVAC system to increase ventilation and filtering.

It is not expected for temperature to have a large impact on air quality in most workplaces. However, it is an important variable to keep track of.

3.4 Atmospheric Pressure

Atmospheric pressure is the force exerted at the surface of the earth by a column of air extending upwards. Average sea level pressure is 101.3 kPa and Mount Everest being higher up is lower at 33 kPa. There are also natural variations in pressure due to weather conditions. Decreasing pressure will be associated with poor weather conditions (storm and rain) and increasing pressure good or stable conditions. Within Vancouver, BC for example, pressure will range from 98 kPa to 104 kPa within the span of a few days.

While weather is interesting, it is not the focus of this project. A health study from Guangzhou, China showed a 1.8% increase risk in non-accidental mortality and a 4% increase in cardiovascular mortality [OU14]. Average pressures in the study ranged from 99 to 103 kPa. PM10 was also higher in the presence of greater pressure, but was accounted for.

Given this data, and the fact we can’t control atmospheric pressure much within an average work environment, pressure is not a critical factor of air quality we need to measure. While it is added to the AQM hardware used for testing, cost can be reduced by removing this sensor.

3.5 Humidity

Excess humidity can occur from improperly vented showers, kitchens, and leaking plumbing. High humidity can lead to other unwanted health issues such as mold and mite growth. Most species of fungi cannot grow unless humidity is above 60% [ARUN86], and can cause not only health issues but property damage as well.

Low humidity is common in the winter when temperatures are cold and heaters are used. Exposure to low humidity will dry out the mucous membrane, increasing the risk of cold, flu and other infections. It is agreed that 30% is too low and 40% is better for the eyes and upper airway [WOLK07]. Additionally, for electronics work, low humidity (<20%) will result in much greater risk of electro-static discharge (ESD) damage. High humidity helps to dissipate static charges by increasing their surface conductivity.

If humidity is too high, a dehumidifier can be used to decrease it. These devices work in the same way an air conditioner does, a set of metal fins or coils is cooled and moisture will condense on the surface. The moisture then drips into a container or drain and is captured.

If humidity is too low, a steam humidifier can be used to increase it. Steam is preferred as it reduces the risk of allergens pumped into the air.

Monitoring humidity is useful feature for the AQM, but would not typically have alarm levels. If humidity were to reach >95% for some time this can indicate a water leak, for example, and an alarm would be tripped. However, there are better equipment available to accomplish this (leak alarms) that can be installed near commonly failing devices (such as water heaters). More importantly is an overall analysis of average humidity in the workplace, over months or years.

3.6 Other

3.6.1 Sound

While sound is not traditionally measured when referring to air quality, it is an important area of health and safety in the workplace. Exposures to loud noise can lead to permanent hearing damage.

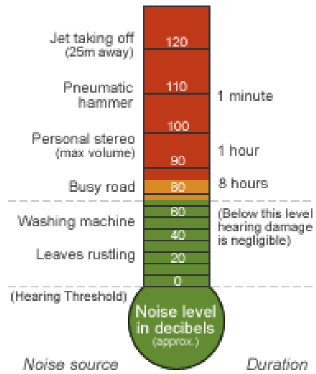


Fig. 3.5 Noise levels and durations prior to hearing damage

When excessively loud sound waves travel into the ear canal, they reach the eardrum and subsequently the inner ear. Inside the inner ear, small hairs vibrate and their vibrations create electrical signals that are passed to the brain. If the sound is too loud, the hair cell can die and bend over, and will never regrow.

With many low-cost micro-electro-mechanical systems (MEMS) sensors on the market, it would not be difficult to integrate a microphone into the sensing module. However, there are two issues with this, location and processing. Processing must be done to categorize the frequencies of interest captured by the microphone. A low frequency signal for example, will not lead to as much hearing damage as a mid-frequency signal (10Hz vs. 3kHz). Location is important as the level of sound measured only matters when near the ear itself. Specifically, the microphone must be placed near the ear of the operator. This is inconvenient and would require a completely wireless device. For this reason, sound is not explored in this project.

3.6.2 Light

Vision is a critical safety requirement in the workplace. Not only can the eye be easily damaged, but temporary blindness means inability to see local hazards (chemicals, sharp equipment) and risks injury. While vision is critical, it is generally clear if eyes are at risk and in most common electronics workplaces can be easily mitigated with a pair of safety glasses. Some exceptions are UV light due to welding or lasers, that is not easy to see, but can still damage the eyes. Monitoring light exposure accurately would also be difficult without using head mounted sensor.

4 HARDWARE DESIGN

4.1 Sensors

Many methods can be used to measure air quality. A sample of measurement methods and their corresponding hardware sensors are listed below.

4.1.1 Particulate Matter

4.1.1.1 Measurement Methods

Light scattering infrared sensing.

The first method of measuring particulate matter is simple and low cost. An infrared diode is lit inside a dark cavity; infrared is chosen as it avoids interference of any daylight that might enter the measurement chamber. Dust passing the sensor cavity will cause reflection of light. The phototransistor measures the reflected light and will output a signal proportional to the density and size of particles. In low cost modules, comparators are used to give estimation of particulate size (PM2.5 or PM10). The comparator will trigger when the photodiode reaches a certain voltage.

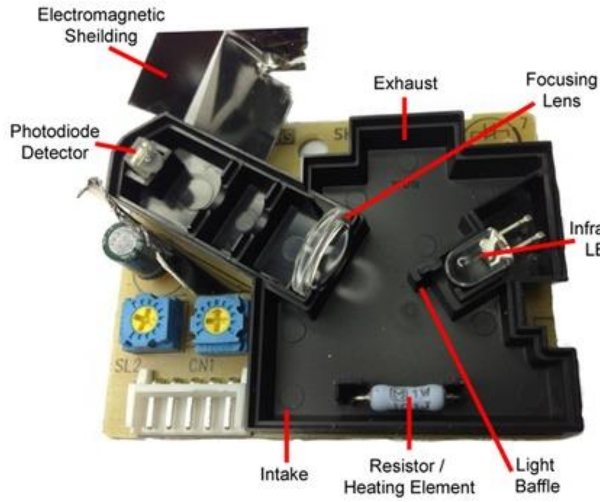


Fig. 4.1. Inside a light scattering particle sensor [ALLA13].

The method is not precise and does require calibration (as can be seen, there are calibration potentiometers on the module). One group from California did get reasonable results from calibration using high quality reference gear [HOLS14]. Air movement is required to cycle air past the sensor, and this is performed using thermal convection. A small 0.25W resistor is powered inside the measurement chamber, causing convection air flow. Since airflow is not controlled precisely or measured, these particulate counts may not be accurate. However, they would still be of use for measuring relative changes in air quality, such as installing filters or observing level of smoke directly caused by soldering.

Laser diode sensor

The laser diode is essentially the same measurement process as with an LED diode. The laser is infrared (~800nm). The laser beam simply provides a more collimated and uniform beam, which allows greater accuracy when differentiating particle size and performing calibration. This also means no optics are required to focus the infrared beam, and the device can be much smaller in size.

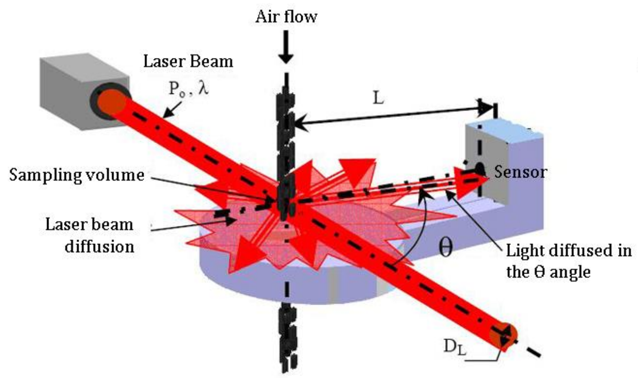


Fig. 4.2: Laser beam particle detection

Weight based measurement

Particles may be trapped by either a sticky pad, or a filter that will trap particles of desired size. Gravimetric analysis is used to determine how much particulate is deposited over a certain time (usually 24 hours). Air flow must be carefully controller or measured to ensure accuracy.

This method uses a large number of disposables (filters or pads) and would require daily manual measurements. This is not ideal for this project as our requirements are for a standalone device with live measurement viewable (for emergency purposes). It is unlikely PM levels would reach a dangerous level in normal circumstances, but live display may prompt users to turn on additional filtration or equip face masks.

4.1.1.2 Available Sensors

GP2Y1010AU0F (Sharp)

Cost:	$5
Range:	0 – 680 μg/m^3
Signal:	Analog (0.9 – 3.4V)
Accuracy:	+/- 30% (estimated)
Power:	100mW
Voltage	4.5 – 5.5Vdc
Size:	46×30×18mm

The GP2Y sharp sensor is an infrared based optical air quality sensor for detecting dust particles. The sensor is very low cost ($4 or less) and would be good for measuring deviation if a large number of sensors are required. However, the accuracy is stated very loosely, so would not make a good reference. Additionally, the sensor output is an analog voltage and would require some signal processing and possibly digital processing (to determine particulate size). It is possible, and would be necessary, to calibrate the sensor from other higher quality modules from other manufacturers [BUDD12] [NAFI12]. Power consumption is very low (under 100mW), and size is compact, so it would be good for a portable device. However, most of the consumption saving is likely due to lack of a fan, so this would need to be provided externally for circulating air (or other methods could be used, or not needed if mounted to a moving object).

PMS3003 (Plantower)

Cost:	$21
Range:	0 – 500 μg/m^3
Signal:	UART (3.3V)
Accuracy:	n/a
Power:	600mW
Voltage	5Vdc
Size:	50×43×21mm

PMS3003 is a compact infrared laser based particulate measurement sensor. PMS3003 has an integrated fan which accounts for the majority of its large power consumption. It also internally analyzes particulate size using a microcontroller. Particulate size is reported over the serial port in three categories: PM1, PM2.5, and PM10 (0.3 to 1μm, 1 to 2.5μm, and 2.5 to 10μm). The device has an internal microcontroller (CY8C4245 ARM M0 32KB), which is capable of relatively complex computations compared to the simple comparator based measurement sensors.

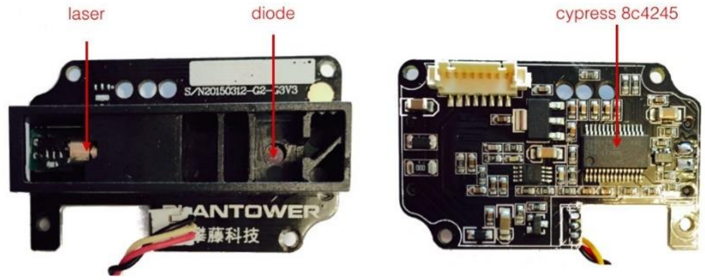


Fig. 4.3 The internal construction on PMS3003 sensor [WAQ15].

The Plantower sensor is unique for low cost sensors in that it will report less than 1μm particle sizes.

PMS7003 (Plantower)

Cost:	$25
Range:	0 – 500 μg/m^3
Signal:	UART (3.3V)
Accuracy:	+/- 10% (100-500μg)
Power:	500mW
Voltage	5Vdc
Size:	48×37×12mm

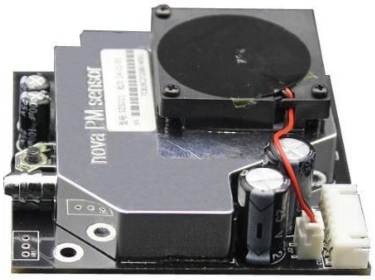
The PMS7003 is an evolution of the previous sensor to reduce power and size. Inside we can see the axial fan has been replaced with a much smaller centrifugal type fan. The processor also shrunk to a QFN package with custom labelling, although it may still be a Cypress part. Real world power consumption was measured incredibly low (210mW).

Fig. 4.5 Top side of PMS7003 showing processor.

Fig. 4.4 Bottom side of PMS7003 showing laser diode and fan.

SDS011 (Nova Fitness)

Cost:	$31
Range:	0 – 1,000 $\mu g/m^3$
Signal:	UART (3.3V)
Accuracy:	5%
Power:	500mW
Voltage	5Vdc
Size:	71×70×23mm



SDS011 is a laser scattering based particulate sensor. The design includes a custom microcontroller and various power supply circuitry as can be seen in the image. A small fan is attached to ensure adequate circulation of sampled air at a known rate. A microcontroller and low noise amplifier is integrated on this sensor (LNA shielded by metal can). The lower noise design likely allows for greater detection of small particles compared to the PMS3003. The large size of SDS011 is not necessarily a disadvantage as capturing greater volume of air will result in more sensitive particulate readings.

The company that produces SDS011, Nova Fitness, was started at university of Jinan, in China. The company is not well known in the west, and products only available from web order (via Aliexpress or Taobao).

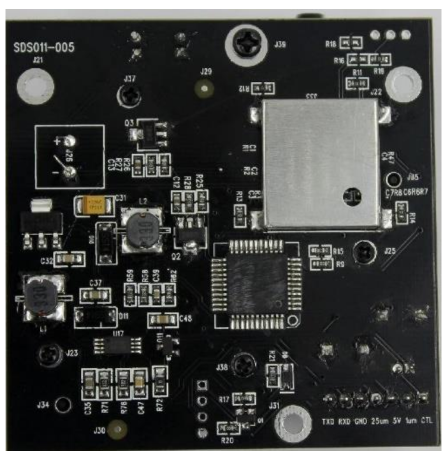


Fig. 4.6: Bottom view of SDS011

SDS021 (Nova Fitness)

Cost:	$39
Range:	0 – 1,000 $\mu g/m^3$
Signal:	UART (3.3V)
Accuracy:	+/- 15% and +/- 10 $\mu g/m^3$
Power:	300mW
Voltage	5Vdc
Size:	42×32×25mm

SDS011 is a laser scattering based particulate sensor. The design includes a custom microcontroller and various power supply circuitry as can be seen in the image. A small fan is attached to ensure adequate circulation of sampled air at a known rate. A microcontroller and low noise amplifier is integrated on this sensor. Shielding is provided by folded sheet metal around the outside of the unit. Counting yield is specified to 70% at 0.3µm and 98% at 0.5µm.

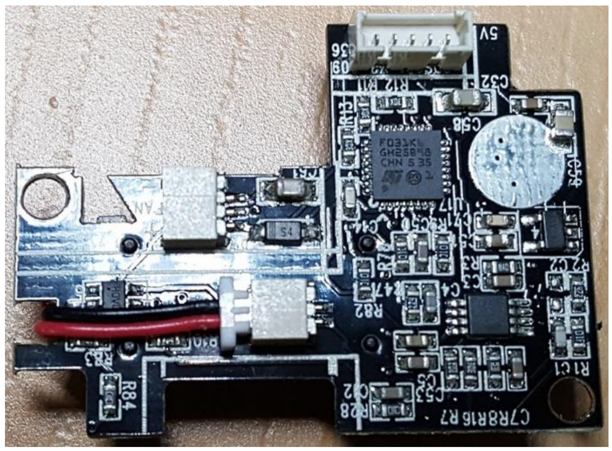


Fig. 1: Inside SDS021 sensor

Above you can see the red and black wires going off to the laser diode, a transimpedance amplifier circuit to amplify the photodiode, and a STM32F103 microcontroller performing sampling. The design is incredibly compact.

4.1.2 Oxygen (O_2)

4.1.2.1 Measurement Methods

Galvanic cell detection

The most common method of sensing oxygen is with a two-lead galvanic cell. In galvanic cell oxygen sensors, oxygen enters via a capillary barrier. The oxygen contacts the cathode (gold or platinum) and is reduced to hydroxyl ions, which enter an electrolyte, into a lead anode. The ions react with the lead anode forming lead oxide. This causes a flow of hydrogen ions between anode and cathode, resulting in a current. Current is produced proportional to the rate of oxygen consumed (Faraday's law of electrolysis). A load resistor is used to convert this current to a voltage which can be more easily measured.

Lifetime of the sensor is limited as the oxidation of lead anode cannot go on forever, when there is no lead remaining the cell will no longer function. Additionally, excess water vapor in the air can pass through the hydrophobic barrier (the one holding the liquid electrolyte in place), causing leakage.

Galvanic cells are not sensitive to changes in pressure, but will significantly change with temperature, up to 1% per degree Celsius [IST05].

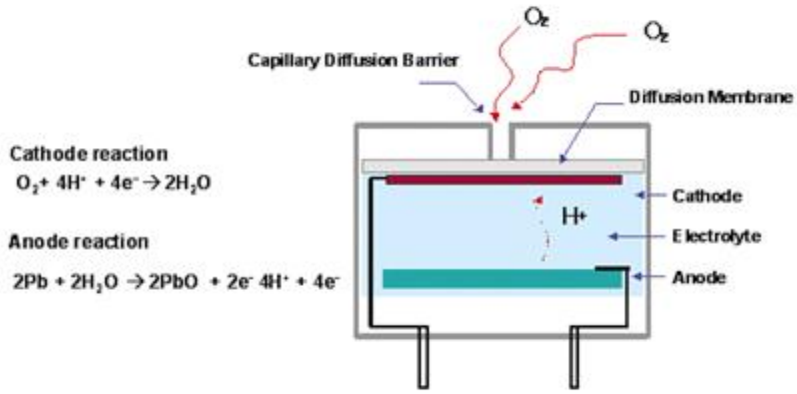


Fig. 4.7: Oxygen sensor components

4.1.2.2 Available Sensors

O2-A2 (Alphasense)

Cost:	\$48
Range:	0 – 20% O_2
Signal:	80 – 120 μA
Accuracy:	-
Power:	-
Response:	<15s
Size:	20×17mm

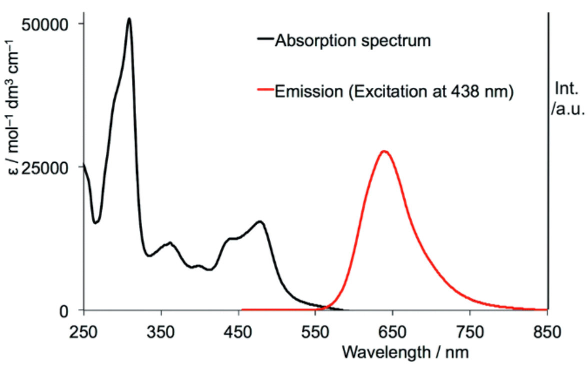
The O2-A2 is a passive oxygen sensor which relies on galvanic cell to produce an output current proportional to the oxygen concentration. Output is a small current which is dissipated in a load resistor (47 ohm), and then measured using an ADC. Output of the sensor will slowly decrease over time. The operating life is specified as >24 months until output reaches 85% of original measured value.

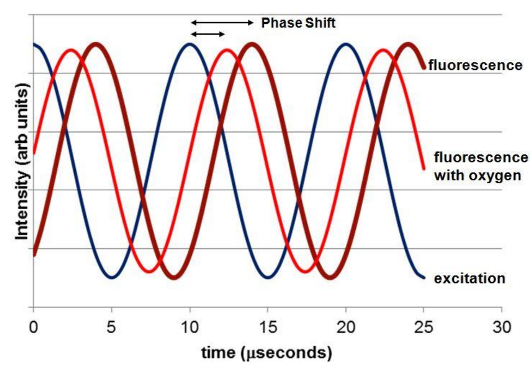
ME2-O2 (Winsen)

Cost:	$54
Range:	0 – 25% O_2
Signal:	150 µA (0 - 15mV with 100Ω load)
Accuracy:	<2% repeat, <2% stability/month
Power:	-
Response:	<30s
Size:	31×17mm

Optical detection

Optical detection of oxygen concentration relies on fluorescence of a sample material. When the material is illuminated with blue light for example, it will produce a red light. In the case of ruthenium complex used in sensors, the emission from a 438nm excitation will be centered around 650nm. This is useful as 438nm can be produced by a blue-green LED. The resulting emission can be measured using a common photodiode. The key to sensing is the light produced will vary in phase shift depending on O2 concentration in the area of the fluorescent material (known as quenching). Note that intensity of output is also reduced slightly. Since no oxygen is consumed in the process of measurement, the sensor lifespan is much longer.





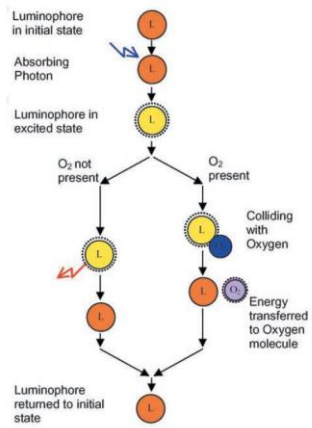


Fig. 4.8 Measuring principle of an optode [TENG03].

LuminOx LOX-02 (SST Sensing)

Cost:	$85
Range:	0 – 25% O_2
Signal:	UART (3.3V)
Accuracy:	<2%
Power:	30mW (85mW peak)
Supply:	4.5 – 5.5V
Size:	12.5×20mm

The LOX-02 uses the principle of fluorescent quenching by oxygen to measure concentration. Internally temperature and barometric pressure are measured to allow self-compensation as sensor values will vary with environment. This allows low power consumption, long lifespan (>5 years), and excellent accuracy.

Due to the relative high cost of oxygen sensors, one was not chosen to be used on the air quality monitor. However, if used LOX-02 would be chosen as it has good accuracy without requiring external calibration. Since the sensor is using UART and 5V supply, it would be possible to connect this to the external serial port of the AQM in place of the particulate sensor.

4.1.3 Carbon Monoxide (CO)

4.1.3.1 Measurement Methods

The common methods of carbon dioxide measurement are electrochemical and catalytic bead.

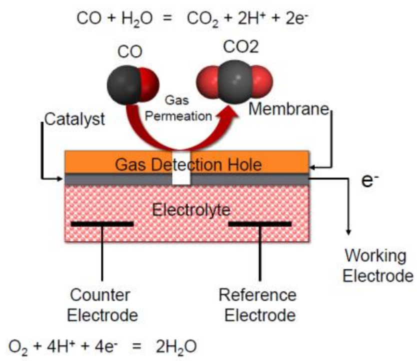


Fig. 4.9 Carbon monoxide electrochemical sensor

In an electrochemical sensor, a small voltage is applied to the reference electrode with respect to the counter electrode, anywhere from 0 to a few hundred mV is common. The gas sensor produces and output current that is in proportion to the gas concentration. This current appears on the working electrode, and is converted to a voltage with a transimpedance amplifier.

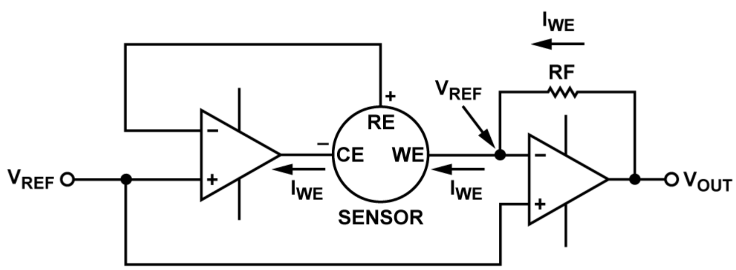


Fig. 4.10 Transimpedance amplifier and sensor in the middle.

Gain of the transimpedance amplifier is set with a feedback resistor, and in the case of 3SP CO sensor, is 100kV/A. In this case, we can use a 100kΩ resistor. This is a very sensitive amplifier, so provisions are taken to reduce noise. After the gas level is converted to a voltage, it can be processed into a digital signal with an ADC. Equation from user manual SDK17:

Cx = 1/M * (Vgas – Vref – Voffset)

Temperature compensation:

Cxc = 1/Mc * (Vgas – Vref – Voffset)

Mc = M*(1+Tc*(T-20))

M = sensor calibration factor, found on the sticker.

Common gas sensors (CO as well as VOC) operate with a suspended ceramic substrate in a metal can. They often run at high power (0.5 to 2W) and have limited lifespan.

On the bottom of the substrate is a coil of nichrome wire, forming the heater. This is surrounded by Al_2O_3 tubular ceramic, to handle the high temperature and act as an electrical insulator. On the top, two wires connect to a sensing circuit whose resistance varies with concentration of applied gas. This is due to the catalyst in the sensing bead allowing the compounds to oxidize, further heating the bead and changing its resistance. External circuitry is required to convert the resistance to a voltage that can be monitored on a microcontroller. One example of this is the MQ3 alcohol gas sensor, shown below.

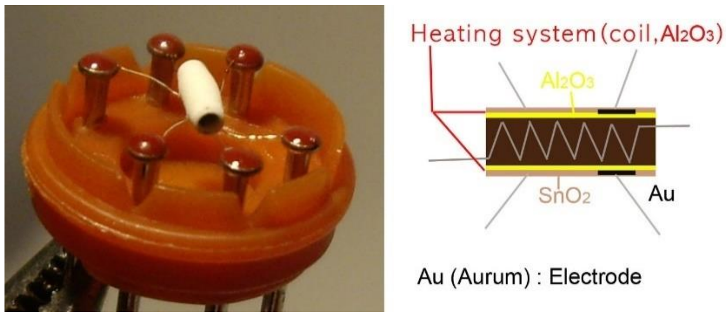


Fig. 4.11. Heated MQ3 gas sensor internal construction [PARK08].

4.1.3.2 Available Sensors

3SP-CO-1000 (SPEC sensors)

Cost:	$29
Range:	0 – 1,000 ppm
Signal:	4.75nA/ppm
Accuracy:	<2%
Power:	10 – 50µW
Response:	<15s
Size:	20×20×3.8mm

The 3SP sensor is a low cost compact electrochemical carbon dioxide sensor from SPEC sensors. It is minimally cross sensitive, that is, presence of other gasses such as carbon dioxide or acetone will not significantly affect the readings of CO. Signal output is a current based on the volumetric fraction of gas present at the sensor (amperometric). Signal output varies between sensors, but is calibrated by the manufacturer and printed on the part. Operational life is greater than 5 years.

External analog circuitry is required to amplify the miniscule currents produced by the sensor (full scale output of 4.75µA).

SPEC sensor is selected as it is low cost, has a long life, and a suitable range for air quality measurement (can measure down to 0ppm).

ZE07-CO (Winsen)

Cost:	$26
Range:	0 – 500 ppm
Signal:	UART or Analog (0.2-4V)
Accuracy:	<3% calibration not stated
Power:	n/a
Supply:	5 – 12V
Response:	<60s
Size:	25×22×20mm

ZE07 sensor is an integrated module based off the ME2-CO electrochemical sensor. The module provides a simple to access data stream, without having to design low level (μA sensitivity) analog circuitry. The cost is about double that of the raw sensor. Lifespan is relatively short at 2 years.

MQ-7 (Generic)

Cost:	$3
Range:	20 – 2,000 ppm
Signal:	2 – 20kΩ
Accuracy:	n/a (calibration required)
Power:	350mW
Supply:	5V
Response:	-
Size:	17.5×16mm

MQ-7 is a very low cost heated tubular sensor, produced by several generic manufacturers. The sensing layer is composed of tin dioxide (SnO_2). The sensor is also highly sensitive to hydrogen gas (equivalent to its carbon monoxide sensitivity). As well as small dependence on various gases such as LPG and alcohol. In the photo above, the element and sensor is enclosed in stainless steel sheet with mesh, to reduce risk of explosion.

TGS2442 (Figaro)

Cost:	$10
Range:	30 – 1,000 ppm
Signal:	13 – 130kΩ
Accuracy:	n/a
Power:	14mW (1W peak)
Supply:	4.8V
Response:	-
Size:	13×9mm

TGS2442 is a compact electrochemical sensor, using a heated sensor inside a metal can. The heater is pulsed at 1W for 14ms every second of operation. Pulsing prevents the migration of heater material into the sensing element as well as reducing average power levels. The TGS2442 is used in some consumer carbon monoxide alarms (First Alert FCD2BT), where it will produce an alarm at 70ppm and up.

TGS5042 (Figaro)

Cost:	$29
Range:	0 – 10,000 ppm
Signal:	0 – 2 µA
Accuracy:	5% (0 – 500ppm)
Power:	-
Supply:	-
Response:	<60s
Size:	50×16mm

TS5042 is a wide range passive electromechanical sensor (up to 1% CO), requiring little supply current. It has some sensitivity to hydrogen gas, as with most other sensors, but is very selective otherwise. The shape resembles that of a standard AA battery.

4.1.4 Carbon Dioxide (CO_2)

4.1.4.1 Measurement Methods

The sensor chosen for CO2 measurement uses a non-dispersive infrared method (NDIR). NDIR sensors work by measuring the amount of light absorbed inside a sample chamber. In the case of CO2, there are three major peaks of absorptivity (Fig. 4.13). The standard peak chosen is 4.23µm, in the infrared band IR-C.

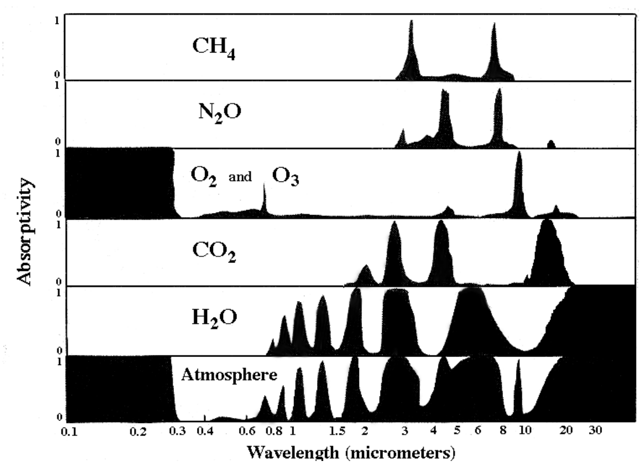


Fig. 4.12 Absorptivity of various gases at specific wavelengths [GREN01].

The IR lamp must be capable of emitting this frequency, and the IR detector must be tuned to receive it. The higher the concentration of CO2 gas in the sample chamber, the more IR is absorbed, and the lower the IR detector will measure.

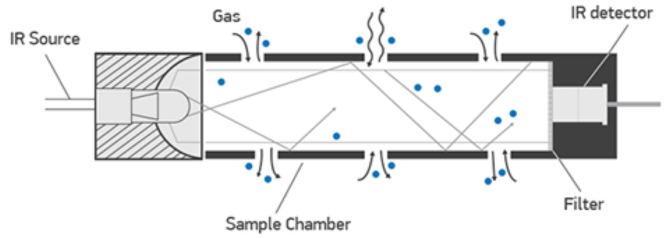


Fig. 4.13 Non-dispersive infrared sensor diagram [ILT17].

Since the IR lamp uses a significant amount of power, it is often pulsed at a low duty cycle. This is acceptable as we don't expect CO2 concentrations to vary rapidly in the period of sub 10s time intervals when measuring a static location. However, if a survey were to be performed, where the sensor module is transported through the environment, our traversal speed would be limited by the slowest reacting sensor.

4.1.4.2 Available Sensors

MG811 (Generic)

Cost:	$30
Range:	350 – 10,000 ppm
Signal:	100 – 600mV
Accuracy:	n/a (requires calibration)
Power:	1.2W
Supply:	6V
Response:	-
Size:	17.5×16mm

MG811 is a low cost compact electrochemical CO2 sensor. The small signal output requires preprocessing to place in optimal range of microcontroller analog to digital converter (ADC), as the output voltage (0.1 to 0.6 volts) is not ideal. Another option is sampling with a very high resolution ADC (16-24-bit). The downside of this is increased sensitivity to noise in the circuit. Noise sources such as the switched DC/DC converter that is used to supply power to the unit, and WiFi.

While the sensor is very small and low cost ($20), the downsides are numerous: high power consumption, requirement of manual calibration, burn in time of the sensor needed to prevent drift [SHEN14]. Another sensor should be chosen which has a stated out of box accuracy, to reduce development time and purchase/rental of calibration equipment.

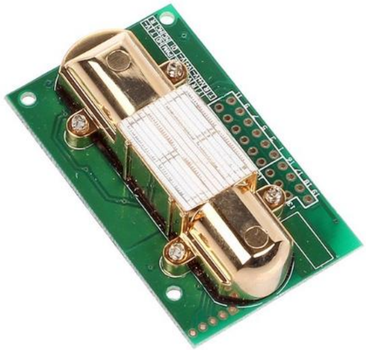
TGS4161 (Figaro)

Cost:	$45
Range:	350 – 10,000 ppm
Signal:	220 – 490 mV
Accuracy:	20% (1,000ppm)
Power:	250mW
Supply:	5V
Response:	90s
Size:	12×9.2mm

TGS4161 is a solid electrolyte CO_2 sensor offering low power and miniature size. A zeolite top filter (microporous aluminosilicate) is used to reduce the influence of interference gases. The TGS4161 is even smaller than the MG811, and would be ideal for a compact personal safety device. However, the accuracy is still not good enough for precise air quality measurement, and suffers the same challenges of signal processing as the other electrochemical CO2 sensors.

MH-Z14 (Winsen)

Cost:	$31
Range:	0 – 2k, 5k, 10k, 30k ppm (optional)
Signal:	UART, PWM, or Analog (0 – 2.5V)
Accuracy:	+/- 50ppm +/- 5%
Power:	<250mW
Supply:	4 – 6V
Response:	<30s (3 min warm up)
Size:	58×35×16mm



MH-Z14 is an intelligent non-dispersive infrared sensor that uses a pulsed infrared lamp for gas detection. Offers a wide range of outputs as there is an internal microcontroller performing sampling and passing on the data. Lifespan is greater than 5 years, as the infrared lamp is much more stable than an electrochemical cell, and allows self-calibration.

MH-Z19 (Winsen)

Cost:	$30
Range:	0 – 2k or 5k ppm (optional)
Signal:	UART or PWM
Accuracy:	+/- 50ppm +/- 5%
Power:	<90mW
Supply:	3.6 – 5.5V
Response:	<60s (3 min warm up)
Size:	33×20×9mm

MH-Z19 is a non-dispersive infrared sensor, containing a built-in temperature sensor, to provide self-calibration of the output signal as it varies with temperature. While this is quite straightforward to perform in a microcontroller (if a manufacturer provided temperature graph is given) it is one less thing to think about.

Available outputs are analog, PWM, and UART. The simplest and best method of transferring data is UART as it will allow direct transmission of the sensors internal processor value to our host sensor microcontroller. If PWM or analog were used, there is a chance of translation error. Timing inaccuracy in the case of PWM, and ADC resolution/absolute accuracy, in the case of analog. Available resolution is an impressive 4ppm.

MH-Z19 is the preferred choice here over Z14 as it has a more compact size, reduced power consumption (90mW vs 250mW), and lower sensor range (2,000ppm) that is more applicable to a typical office environment.

The manufacturer of the product is Winsen Sensor. Oddly the datasheet is not branded with any manufacturers name or logo, which is slightly concerning. However, favorable comparison data is available with the similar form factor sensor (SenseAir S8 from Sweden).

4.1.5 General Air Quality

AS-MLV-P2 (AMS)

Cost:	$38
Range:	10 - 1,000+ ppm (various)
Signal:	50 to 500kΩ
Accuracy:	-
Power:	34mW
Supply:	2.7V
Response:	-
Size:	9×9×4.5mm

The AS-MLV-P2 is a compact micro-electro-mechanical systems (MEMS) based sensor, designed to detect a wide range of gases. Power consumption is low even for a heated sensor operating at 300°C, only 34mW. Gases include carbon monoxide, butane, methane, ethanol, and hydrogen.

Downsides are, as with most heated sensors, a very long burn-in time is required before use (120 hours). Additionally, the broad range of gases detected make air quality analysis difficult. As a consequence, this sensor would be useful for an alarm or alert system but not this project.

4.1.6 Temperature

Temperature is relevant to our study for a few reasons. Most importantly it is necessary to perform calibration of the SPEC carbon monoxide sensor chosen. When the CO sensor is exposed to warm or cold temperatures, its output will shift and it is necessary to accommodate for that with an accurate temperature sensor.

4.1.6.1 Design Notes

Since the board is consuming power, the temperature of the entire board will be above ambient. Hottest near the power consuming components (such as linear regulator and microcontroller), and tapering out from these points.

A few methods can be employed to mitigate this. One can calibrate the sensor at a given ambient temperature, and subtract the rise in temperature due to nearby heat sources. However, this becomes complex when you consider that the processor may be sleeping, resulting in reduced power draw, or air flow may be present, resulting in greater/less board to ambient temperature.

The simpler and more effective method is to isolate the sensor as much as possible from the board. This means ground planes around the temperature sensor can be removed, and a cutout is made, providing insulation in the form of an air gap. Below is a view of what this would look like.

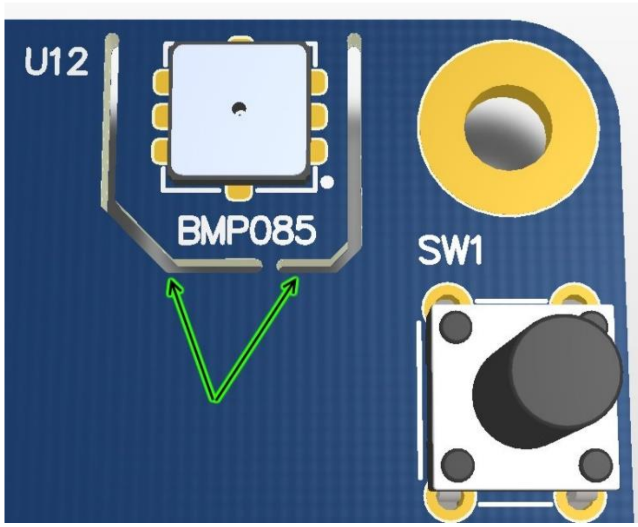


Fig. 4.14. Arrows point to the isolation slots to reduce heat transfer from board to sensor

Temperature is often measured in conjunction with humidity, see below for humidity sensors and available options.

4.1.7 Atmospheric Pressure

4.1.7.1 Available Sensors

BMP085

Cost:	$2.90
Range:	30 kPa – 110 kPa
Signal:	I^2C two wire
Accuracy:	+/- 100 Pa
Power:	10uW standby, 40uW active
Conversion:	26ms
Size:	5×5×1.2mm (CLCC)

4.1.8 Humidity

Combined humidity and temperature sensors are a commodity and are available with relatively good resolution and in a compact size. An I^2C based sensor was chosen to simplify communication and reduce the number of I/O necessary from the microcontroller.

4.1.8.1 Available sensors

SHT11 (Sensiron)

Cost:	$17
Range:	0 – 100% humidity
	-40 – 123 °C
Signal:	Serial two wire
Accuracy:	+/- 3% RH, +/- 0.4 °C
Power:	5uW standby, 3mw active
Response:	8s
Size:	7.5×5×2.5mm (SMD-8)

SHT11 is a very popular combination humidity and temperature sensor.

Downside of this part is it is not I^2C compatible, so you cannot use hardware I^2C to communicate with it. This means greater overhead and complexity in software as the microcontroller will need to toggle I/O pin manually to generate a clock. Using a hardware I^2C peripheral, it can automatically generate the clock and send out data in the background, while the main processor is free. This is an older part, and compared to other sensors uses relatively large amount of power (3mW). SHT21 is available as a SHT11 equivalent but with I^2C compatibility.

SI7006/SI7020/SI7021 (Silicon Labs)

Cost:	$1.50 - $2.70
Range:	0 – 100% humidity
	-40 – 125 °C
Signal:	I^2C two wire
Accuracy:	+/- 3% RH, +/- 0.4 °C
Power:	0.2uW standby, 500uw active
Response:	18s
Size:	3×3mm (DFN-6)

SI7021 is a compact humidity and temperature sensor with I^2C interface available in a handful of grades.

For maximum resolution, a temperature reading will take 11ms and a humidity reading will take 12ms. These times are not too significant if one reading per second or less is performed (~2.5% of processing time). If additional processing time is needed, separate start/end conversion functions can be implemented in software so the processor does not have to wait on conversion.

The SI7021 also has an integrated heater, controllable from 10mw to 300mW. This allows condensation to be driven off, and to verify the sensor is working.

4.2 User Interface

The goal of this hardware design is to create a simple easy to interpret user interface. It should not be required to be familiar with technical terms to operate the device. It should also not be necessary to constantly monitor or observe the device.

Requirements:

- If a sensor is to fail, the screen should display error code.
- If an environmental concern is measured, unit should alert user both visually and via audio.

Display:

- An OLED screen was chosen as it has good visibility, and is very compact and simple to operate.

Audio:

- A simple piezoelectric buzzer is used to alert the user if a sensor reading enters an unsafe range. Function like that of a common household fire alarm.

4.3 Microcontroller

A microcontroller is necessary in the AQM design to read signals from environmental sensors, process the data, and display data to a screen. Due to the large number of available options, a few were chosen to give a representative example of the broad choices that need to be made.

4.3.1 Feature set comparison

Comparing the three chosen processors, we see a good range of selection available. From low cost and subsequently limited memory, to high cost and performance.

	Atmega328P	STM32L476RGT6	Raspberry Pi 3
Speed	20 MIPS (20MHz)	100 DMIPS (80MHz)	2,500 DMIPS (1.2GHz) ×4 cores
Flash	32KB	1MB	2GB+ (microSD)
SRAM	2KB	128KB	1GB DDR2
ADC	1×10-bit (8 channel)	2×12-bit (16 channel) 5.3 MSPS	-
DAC	-	2x12-bit	-
GPIO	23	51	26
UART	1	6	1
Supply voltage	1.8-5.5V	1.7-3.6V	5V
Cost (1,000 qty)	$1.85	$6.06	$45
Packages	32-TQFP, 32-VQFN	64-LQFP	85×56mm module
Other	RTC, I2C, PWM, TIM	RTC, Opamp, SDMMC, USB, PWM, SPI, RNG, 17xTIM	PWM, I2C, USB, WiFi, Ethernet, Bluetooth

Table 4.1. Specification comparison of processors.

The omission of an ADC on the Pi3 is concerning, but if chosen an external ADC could always be added. More of an issue is the large size and cost of the board.

The SRAM on the Atmega controller is too low to hold a reasonable number of storage samples for analysis. Additionally, lack of flash is concerning for user interface elements such as fonts and graphics. The STM32 has more than enough RAM and flash for what this project will encompass. Lower end (256kB, 512kB flash) and pin compatible models are available, if cost savings is necessary.

Having the 6 UARTs is quite useful as some of our available gas sensors use that for communication. Dedicating a UART to each device simplifies design and reduces chance of communication errors like collision.

4.3.2 Power consumption comparison

The greater performance of the Pi3 (about 25x) comes at a cost of 36x increase in power consumption. However, if the design has any chance of being a portable unit, it must have a reasonable run current. 1.5W is far too high, but both microcontroller options are a reasonable sub 100mW.

	Atmega328	STM32L476RGT6	Raspberry Pi 3
Voltage	3.3V	3.3V	5V
Running (all peripherals)	12mA (40mW)	29mA (96mW)	310mA (1.55W idle) 700mA (3.5W full load)
Running (no peripherals)	~7mA	10mA	220mA
Sleep (RTC running)	0.9uA	0.4uA	~50mA
Efficiency (MIPS/mW)	0.5	1.04	0.71

Table 4.2. Power consumption comparison of processors

4.3.3 Microcontroller vs microcomputer

Microcontroller can generally be considered a device that runs with minimal or no supporting components. Most modern microcontrollers are capable of running with a handful of supporting passives (resistors, capacitors) and can derive a clock from an internal oscillator. Additionally, they come with a wide variety of integrated peripherals. Analog to digital and digital to analog converters, serial transceivers, programmable gain amplifiers, timers, and even programmable logic may be integrated. This integration can simplify design and reduce PCB complexity. However, integrated peripherals can rarely match the capability of external devices, as the manufacturing process is optimized on a per device basis.

A microcomputer will have supporting parts such as external RAM and flash. These devices have become very popular with the advent of Raspberry Pi. Competition means boards are available for well under $50 (Orange Pi available for $15). While these allow more horsepower, it comes at the cost of additional power consumption, board space, and price. Generally, the microcomputer board will run a full operating system, such as Ubuntu Linux.

	STM32L476 (minimal implementation)	Orange Pi Zero Mini	Raspberry Pi 3
Dimensions	20×20×5mm	48×46×17mm	56×87×19mm

Table 4.3. Size comparison of processor modules.

4.3.4 Fixed point versus floating point

Embedded microcontrollers typically operate using fixed point numbers such as 8 or 16 bit. This matches well with the digital peripherals and sensors they communicate with. An ADC may have a resolution of 8 or 12 bits, a digital temperature sensor 10-bits. The microcontroller can store and process these values with ease, even multiplying or dividing without much issue.

The problem comes when data needs to be displayed to the user, a 10-bit temperature value such as 0x2FA is not human readable. It must be converted to floating point (23.244C) before it is of use to us.

Since we require some level of interaction with the sensor module, having a floating-point conversion or processing internally will be necessary. With an 8-bit processor such as the Atmega328P, performing a IEEE 754 single precision (32-bit) floating point division can take hundreds of CPU cycles. In comparison, on the STM32 or Pi, hardware floating point support allows one or two cycle multiplication. This is known as a floating-point unit (FPU).

	Atmega328P	**STM32L476RGT6**	**Raspberry Pi 3**
Core	Atmel AVR	ARM Cortex M4	ARM Cortex A53
Multiply	8-bit	32-bit	32-bit
FP precision	-	single precision	single and double
Floating-point unit	no	FPv4-SP	ARM 1176 VFP
DSP instructions	no	yes	yes

Table 4.4. Arithmetic comparison of processor cores.

4.3.5 Estimated memory requirements

Microcontroller flash space estimation:

Microcontroller (Flash):

- SDMMC library = 10kB
- FatFs filesystem library = 10kB
- Code for main operation/sensors = 10kB
- Font for displaying readings to user = 5kB
- Graphics for display = 5kB
- Total = 40kB

Microcontroller (SRAM):

- Storage of all readings for the past 24hr = 23kB
- Global variables, sensor calculations, etc. = 5kB
- Framebuffer for 128x64 LCD = 1kB
- FatFs buffer = 0.5kB
- Total = 29kB

4.4 Supporting Components

Voltage reference (LM4120A)

To be able to measure a consistent and accurate level from the microcontrollers ADC it is necessary to use an accurate voltage reference. The STM32L476 does include an internal reference with the following specifications:

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
V_{REFINT}	Internal reference voltage	–40 °C < T_A < +130 °C	1.182	1.212	1.232	V
$t_{S\_vrefint}$ (1)	ADC sampling time when reading the internal reference voltage	-	4(2)	-	-	µs
$t_{start\_vrefint}$	Start time of reference voltage buffer when ADC is enable	-	-	8	12(2)	µs
$I_{DD}(V_{REFINTBUF})$	V_{REFINT} buffer consumption from V_{DD} when converted by ADC	-	-	12.5	20(2)	µA
ΔV_{REFINT}	Internal reference voltage spread over the temperature range	V_{DD} = 3 V	-	5	7.5(2)	mV
T_{Coeff}	Average temperature coefficient	–40°C < T_A < +130°C	-	30	50(2)	ppm/°C
A_{Coeff}	Long term stability	1000 hours, T = 25°C	-	-	TBD(2)	ppm
$V_{DDCoeff}$	Average voltage coefficient	3.0 V < V_{DD} < 3.6 V	-	250	1200(2)	ppm/V
V_{REFINT_DIV1}	1/4 reference voltage	-	24	25	26	% V_{REFINT}
V_{REFINT_DIV2}	1/2 reference voltage		49	50	51	
V_{REFINT_DIV3}	3/4 reference voltage		74	75	76	

Table 4.5. Embedded internal voltage reference.

If the internal voltage reference is configured to use the manufacturers supplied calibration value, absolute voltage is not a concern. So, it is only necessary to consider the temperature and voltage effects. Assuming our 3.3V supply is stable, worst case accuracy is determined by the 7.5mV temperature variation:

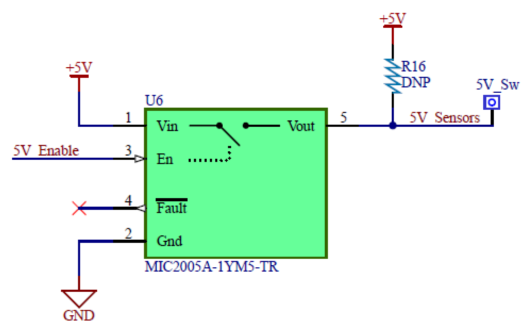
7.5mV / 1.212V = 0.6%

From this point we need to scale up to the VADC voltage used, in this case 3.3V from the main supply can be used. This brings error closer to 2%.

In case this is an issue, a more accurate voltage reference was chosen, the LM4120. This chip provides an accuracy of 0.2% for our reference (3.3V).

Current limiting switch – MIC2005A

When using external sensor modules, it is useful to have a way to turn the sensor on and off. Either to save power, or to reset the module in case of unexpected failure. The MIC2005 high-side switch is used to supply 5V to the external sensor modules, as well as protect from overcurrent. The 2005A will automatically shut off the output if overcurrent is seen (>0.5A).



Analog front end – LMP91002

The chosen carbon monoxide sensor is an amperometric sensor with a very low output current (nanoamps, see section 4.1.3.2). To be able to interface this current output with our microcontroller we will need to convert it to a voltage, and amplify it massively. Traditionally a transimpedance amplifier circuit is used to do this, as seen below.

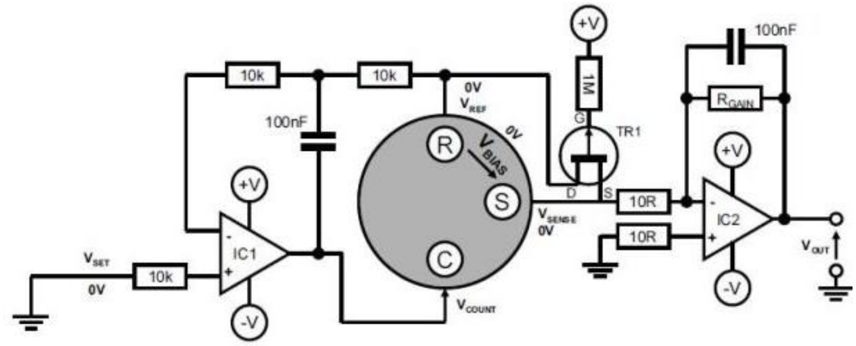


Fig. 4.15. Typical transimpedance amplifier.

IC1 applies a voltage to the Count electrode such that the Reference pin is held constant (in this case at 0V). IC2 provides the gain necessary, in our case with a peak sensor current of 4.75μA for CO-110 an ideal gain is: 3.3V / 4.75μA = 695kΩ/V. With currents this low and large gains, opamp choice and layout is critical. To reduce complexity of the design a complete analog front end is chosen, LMP91002.

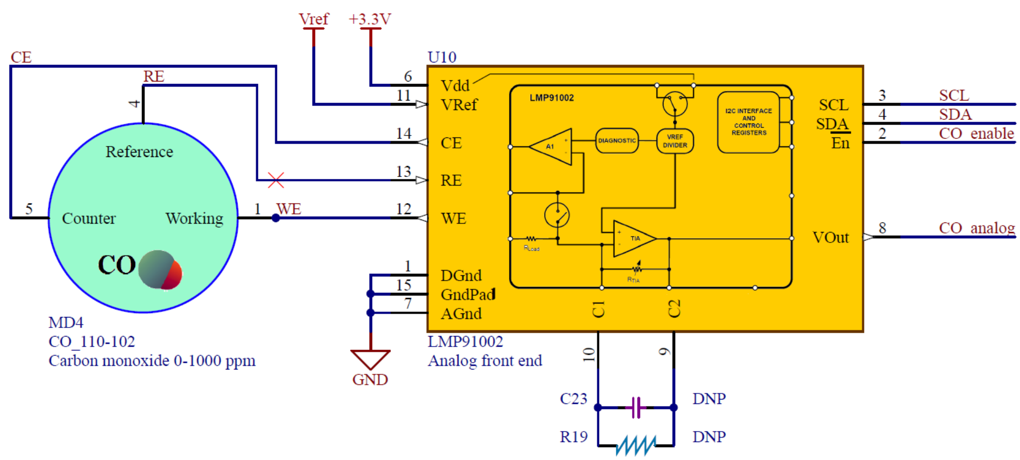


Fig. 4.16. Carbon monoxide sensor and amplification circuit.

Inside the LMP91002 is a transimpedance amplifier circuit, shorting FET, and reference voltage, all the components we saw previously. The LMP91002 is controlled via I^2C, which lets us apply several preset gain resistances or even apply a diagnostic offset for testing presence and function of the gas sensor. LMP91000 is also available with an internal temperature sensor, but is not necessary and cost is $1.10 greater in quantity. Interestingly it was found that LMP91000 and LMP91002 are functionally identical, so must be using the same silicon.

4.5 Crystals and Resonators

An accurate method of timekeeping is necessary on the AQM board to date stamp logging information. This is important to correlate outside actions with air quality readings.

The standard method of reference is a quartz crystal, which is a thin piece of quartz that has been cut to specific dimensions to produce a precise resonant frequency.

The ceramic crystal chosen is the AB26TRQ-32.768KHZ-T from Abracon. A small (7x1.5x1.5mm) surface mount part available for about $0.33. Accuracy of a crystal is given in ppm, the AB26 has a rating of +/- 20ppm. Over a week this would give a worst-case time error of 12 seconds. Adequate for our purposes of correlating measurements.

Fig. 4.17. Surface mount crystal

4.6 Wireless Communication

Wireless communication would provide a number of benefits useful in the AQM:

- Remote access (convenient)
- Reduce health risk in toxic environment
- If monitoring work site for individuals who are focused on the job, and don't need another task (checking sensors)

Two wireless protocols were chosen (ZigBee and WiFi). To perform the heavy lifting tasks of wireless communications (collisions, data corruption, interference and encryption) integrated modules are chosen. This means a slightly higher cost, but much shorter development time. Two popular modules for communication were compared:

	ZigBee (CC2530)	WiFi (ESP8266 in 802.11b mode)
Tx power	4.5dBm	20dBm
Rx sensitivity	-97dBm	-91dBm
Tx current (at peak)	40mA	170mA
Rx current (at peak)	30mA	56mA
Sleep (AP connected)	0.2mA	0.9mA
Range (ideal, with LOS)	400m (antenna)	370m (PCB antenna)
Peripherals	-	ADC, IR, SDIO,

Table 4.6. Comparison of two wireless modules

Current consumption is stated at 3.3V. Range is ideal with line of site (LOS).

CC2530

The selected ZigBee (IEEE 802.15.4) device is CC2530 from TI. Available in a QFN40 package with minimal external components required. Module is based off an 8051 core, with internal 8kB RAM. Cost is low, $4 in quantity.

ESP8266

The ESP8266 is a highly integrated low cost WiFi on chip produced by Espressif in China. Originally introduced in 2014 for less than $4, it has become very popular among hobbyists.

The chip can currently be purchased for $2 but is most commonly sold online as a standalone module. The modules contain ESP, flash memory, crystal, LEDs, and some form of antenna. Once programmed and externally powered, the module can be a complete standalone wireless node.

The ESP is available in QFN32 package, relatively compact but still easy to solder and layout on a 2-layer board. Die size is 2050x2169μm, seen below. 50% of the chip consists of a wireless transceiver and power amplifier (PA), 25% is memory, and 25% is CPU core.

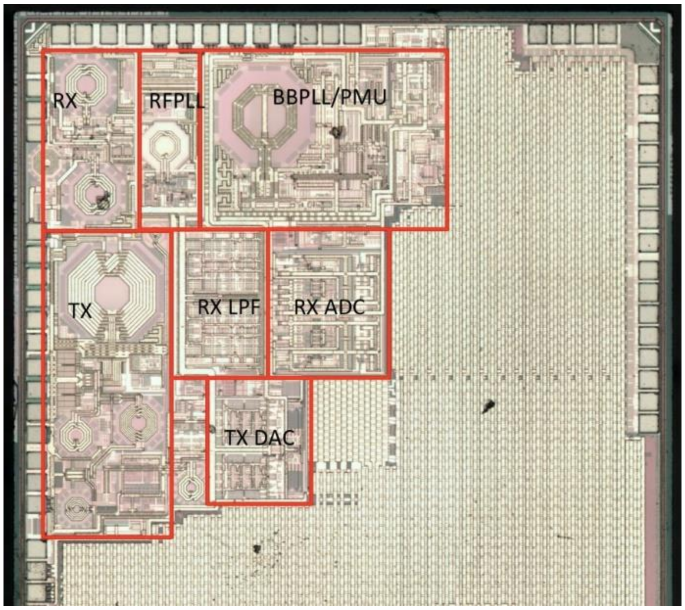


Fig. 4.18. Die shot of the ESP8266 and highlighting of RF sections [ZEPT14].

The CPU core is an 80MHz 32-bit RISC processor, Xtensa developed by Tensilica. The number two 32-bit processor on the market. To process the WiFi stack, approximately 20% of the CPU cycles are used, so that leaves a lot left over for general purpose monitoring or serial communications to a host microcontroller. Die image above was produced by Zeptobars, outside package was dissolved using boiling sulfuric acid.

4.7 External storage

External storage is necessary to hold sensor information for our device to be useful. Instantaneous data is useful for dangerous warnings, but not for long term study or hazards.

4.7.1 Storage Requirements

Requirements that had to be met:

- Non-volatile, as the device could lose power due to outage or misuse, and we would not want to lose sensor data
- Low voltage operation
  - Ideally the memory would operate at the same voltage as the host microcontroller (3.3V), to avoid the use of level conversion
- Low power operation
- Standard bus communication
  - The host has following protocols supported in hardware: I2C, USB, USART, SPI, SDMMC

- Low number of I/O

Removable:

- Removal allows ease of a sensor installer dropping off the device, and coming by to swap out the internal memory device with a blank.
- Ideally the device would transmit wirelessly, however there is the possibility of networks going down or data being lost in this process. It is always prudent to have a backup storage method and a relatively simple way to access that data (logs or sensor).

4.7.2 Estimation of storage requirements

System estimations:

- 16-bit value recorded once per minute
- 8+ sensors
- Able to hold one month of data
- May be less if ability to transfer data wirelessly is reliable
- May be relevant to battery life

Estimation of required capacity:

- If 10 sensors are used, one reading per second, with 64-bit precision (8 bytes total), a month worth of data would consume:
    - 10*1*60s*60min*24hr*30day*8 bytes = 207MB
- This excludes any diagnostic or logging information, and assumes binary formatting of the data. To allow simple access to the data, this is not ideal (conversion tools or script would be required). Ideally the data would be stored in CSV or similar human readable format.

A small selection of popular embedded device memories was chosen.

	Secure Digital (SD card)	Serial EEPROM	Serial Flash
Capacity	1MB to 2TB	1KB to 256KB	32KB to 32MB
Cost	$5 (8GB)	$2.50 (256KB)	$1.60 (16MB)
Example device	Adata AUSDH8GUICL10	STM M24M02-DRMN6TP	Winbond W25Q128FVSIG
Speed	10MB/s	125KB/s	50MB/s
Bus	SDMMC, SPI	I^2C	SPI, QPI
I/O required	3 to 7 (SDMMC), 4 (SPI)	2	3
Removable	Yes	No	No
Dimensions	15×11×1mm (microSD) 15×12×1.55mm (card slot)	6×5×1.75mm (8-SOIC)	6×5×1.75mm (8-SOIC)
Current consumption	66/85 mA (read/write) 132 uA (standby)	2.5 mA (read/write) 5 uA (standby)	20/25 mA (read/write) 50 uA (standby)
I/O voltage	2.7 – 3.6V	1.8 – 5.5V	2.7 – 3.6V
Write cycles	~10,000	4,000,000	100,000
Photo			

Table 4.7. Comparison of storage memory types

4.7.3 SD (Secure Digital)

SD is popular as it is used in numerous consumer electronics devices, and there are many manufacturers of SD cards. The most common current form factor for SD is microSD (15×11×1mm). While larger than the EEPROM and Flash chips available, it is still compact enough to fit in this project.

One downside of commodity cards is that it can be difficult to ensure the purchased card is legitimate, as many sellers have been found to produce counterfeit cards [HUAN10]. These cards may not have the fully advertised performance, capacity or reliability of the original manufacturer. It is possible for them to enter the supply chain at almost any level.

The holder for the microSD card is compatible with typical electrical manufacturing processes (SMD reflow soldering). Example dimensions were taken from Amphenol 114-00841-68. However, the memory itself would need to be manually installed in the device prior to testing.

The SD communication protocol is quite complex due to the number of manufacturers of cards and what features they support. The host must initially communicate with the SD card at a low clock rate (~400KHz), to allow legacy devices to respond. During this initial phase, it requests several status codes: manufacturer ID, card size, block size, voltage supported, speed class, and more. Depending on the response, writing to the card may require different processes, so all of these codes must be taken into account for reliable operation. The result of this is that SD code is quite complex, and not something one would write as part of their project. In this case, we can rely on STMicroelectronics software modules (STMCubeHAL), which contains a SDMMC driver.

SD hardware communication is similar to SPI, there is a clock connection running to the card. This clock is generally left running during operation. Data is sent from the host to SD on the MOSI line, and data is returned on MISO. If the single bit bus is not fast enough at its supported clock speed (25-50MHz, or about 6MB/s), additional data lines can be connected. This widens the bus to a maximum of 4-bits, increasing the throughput four-fold.

4.7.4 Serial EEPROM

Electrically erasable programmable memory (EEPROM) is a time-honored method of non-volatile storage, in use since the 70's. EEPROMs store data in arrays of floating gate transistors. Along with FRAM, serial is available in very small packages (3.6×2×0.45mm or less).

EEPROMs allow single byte erase and write, which works well with small devices as the amount of data to be written is often only a few bytes (such as a few bytes storing number of power on cycles, or calibration data). The same bytes, unlike flash, can also be written millions of times. This is ideal for simple storage of configurations, but the downfall is its limited capacity. EEPROMs are seen most often in a few KB up to hundreds of KB. For continuous logging, we can see below it would quickly be filled:

256KB / 8bytes/s = ~9 hours of data.

If a wireless link were to go down, it would not be desirable to have to get to the logging module within 9 hours to ensure no important data is lost.

Hardware interface is most commonly I2C or SPI, simple protocols found commonly on the majority of microcontrollers. I2C requires two connections, one for bidirectional data, and one clock. While SPI adds a chip select control line, and splits data into two directions (MOSI/MISO). Data can be written by simply addressing the EEPROM with write bit enabled, at the correct clock speed, and then streaming data in.

4.7.5 Serial Flash

Serial flash is similar to EEPROM in many ways, but has much greater density resulting in lower cost for a larger amount of storage (up to 32MB is available). Serial flash is ideal for write once, read often, such as storing firmware or FPGA configurations, which are streamed into the chip upon boot.

Instead of writing/erasing individual bytes it must be written to in pages. Pages are in the range of 512bits in size.

4.7.6 FRAM

FRAM is ferroelectric random-access memory, similar in operation to DRAM. It allows a large number of writes and data retention like EEPROM, but offers higher speed (2.5MB/s vs 125KB/s). Is available in limited size ranges (2kB to 512kB). Capacity is limited so is not enough for us in this application. FRAM is more appropriate in data critical applications, where the device could lose power at any time, and some state of the system needs to be saved.

4.8 Circuit board

4.8.1 Component Placement

Good component placement will result in simpler PCB trace layout and an overall better product. In some cases, placement is driven by external factors. Connectors, LEDs and switches, must be placed on edge of board or where a user can easily access them.

Placement of passive components and IC's within the board is more freely controlled by the designer. Good placement will take into account routing complexity as well as aspects such as coupled noise and loop area. Loop area is the encompassed area within the current path of a signal. Below is an example of large loop area (left) and the same circuit with reduced loop area (right).

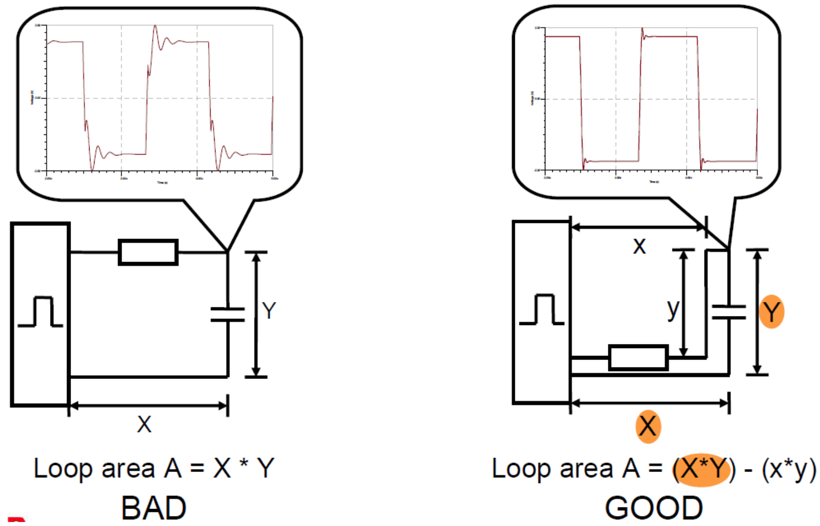


Fig. 4.19 PCB Layout for Switching Regulators – TI

Connectors (power and external sensor) were placed on the left side of the board. Display was placed to the center-right of the board.

Buttons are placed on the right-hand side of the board for easy access (for right-handed user). Removable microSD card holder is placed along the top of the board. This allows quick swapping of the card; however, it could be bumped loose. Future design would use a locking connector (push to insert, push to release type).

4.8.2 Bypass Capacitors

The purpose of capacitor decoupling is to shunt RF energy away from a power pin to ground. A 0.1uF 0402 X7R capacitor can be purchased in quantity for less than 1c. Ensuring each IC has adequate bypassing is cheap insurance for producing a reliable low noise device. One capacitor should be placed on each IC's power pin at minimum.

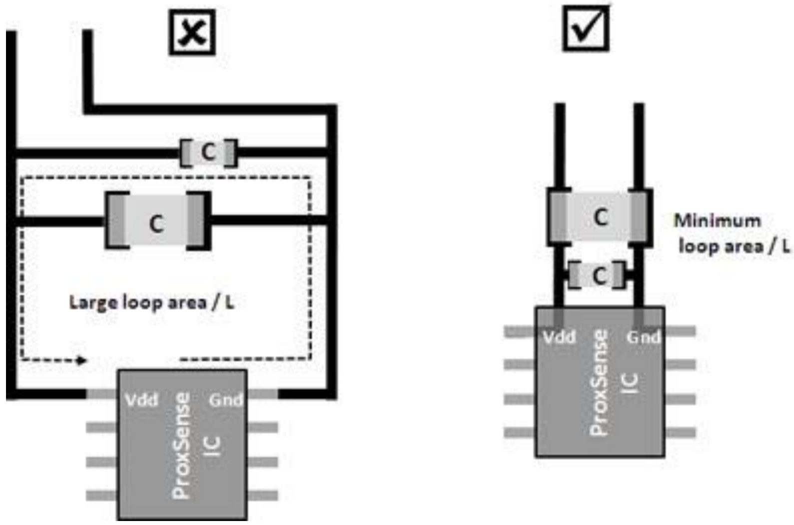


Fig. 4.20 Placement of bypass capacitor to minimize loop area [JDVA12].

4.9 Power

4.9.1 Requirements

The design for AQM uses several components at various voltages, primarily 3.3V for processor and IC's and 5V for sensor modules. An external power supply of 5V could be chosen for simplicity, however, if this is done we are relying on the supply to provide an accurate low noise output. This is costly and may require a lot of trial and error, as generic wall supplies do not provide extensive specifications. USB power would be simple and easily available, but is not suitable. A USB supply can vary from 4.4V to 5.25V, not an ideal scenario when we want stable sensor readings. Also, current available

4.9.2 Power Consumption Estimations

Total power consumption needs to be known as our supply must be capable, or the device could shutdown unexpectedly. It is also useful to know if the device were to be operated from rechargeable batteries, knowing consumption will give us an estimated operating time. Individual components were powered and consumption was measured with a lab power supply where possible. See section 15 APPENDIX F: MEASUREMENT DATA for specific measurements.

Component	Peak current	Average current
	5V	
SDS021 (particulate)	80 mA	72 mA
MH-Z19 (CO2)	224 mA	15.5 mA
	3.3V	
OLED display (1.3")	46 mA	26 mA
ESP-01 (WiFi)	330 mA	35 mA
LED*4	8 mA	4 mA
STM32L4	19 mA	5 mA
Other	<1 mA	<1 mA
Total	708 mA	159 mA

Table 4.8 Current consumption of components, running on 3.3 or 5V.

Total power consumption is the sum of all currents in current consumption table multiplied by 5V (as a linear regulator is used to provide 3.3V, current in from 5V is equal to current out): 3.5W peak and 0.8W average. Assuming 80% converter efficiency, this would rise to 1W average.

A standard 18650 lithium cell is rated at 3.8V and 2500mAh. It can therefor produce 2.5A*3.8V = 9.5WHr. If average consumption is 1W, the device would last 19 hours on two cells. Adequate for daily monitoring of an employee or taking on a survey.

4.9.3 Efficiency

Efficiency is important for several reasons; increased efficiency means less heat dissipated in the power supply section and likely greater life. It also will result in longer battery life (however this can be a tradeoff with quiescent current).

AOZ1280 was chosen partially due to its large claimed datasheet efficiency (up to 95%). The power supply was assembled and tested using various loads (resistive and constant current). Results can be seen in section xxx. A peak efficiency of 89% was measured at 500mA output current (12V in), this is near the expected operational current range (300-500mA).

Input voltage vs. efficiency was measured and found to not vary significantly between 6 and 15V (~87%). Above these voltages, efficiency drops slightly to 84%. 12Vdc is chosen as the AC/DC wall plug supply voltage, as it is commonly available.

Efficiency of the AQM design must be considered as we do not want excess heat to affect our sensor readings (temperature, humidity, and possibly more). It also needs to be considered if the device were to run from battery for any significant time (mapping outdoor areas for example).

Linear regulators

A linear regulator drops input voltage down to its output, with no change in the current. The difference between input and output voltage is across a transistor inside the regulator.

NPN in a standard regulator or often PNP in the case of a low dropout (LDO). This excess voltage is dissipated as heat in the transistor. As a consequence, stepping down a large voltage is not efficient.

Switching regulators

A switching regulator was chosen to step down the input voltage, as it increases the current. Efficiency of switching regulators can be high even given small or large voltages. However, they are more costly and complex than linear regulators.

Buck regulator

A buck regulator is a circuit that drops the voltage down. Producing greater current at its output. It is more efficient than a linear regular (80% or more). From the above information, a step-down regulator is chosen (AOZ1280), allowing an input voltage source from 9 to 24V which is stepped down to an accurate 5Vdc and filtered. The regulator operates at a fixed frequency of 1.5MHz. Pulse width modulation (PWM) is used to adjust the on and off time of the switching element.

4.9.4 Noise and Accuracy

The amount of noise produced by the power supply will influence accuracy of our measurements and in extreme cases can cause our circuit to not work. Linear regulators are very low noise, whereas a switching DC regulator will have a greater amount of noise.

In this case the best option is chosen where appropriate in the circuit. A 5V switch-mode supply is used to power the high current drain devices (particle sensor with fan, co2 sensor with lamp). A lower noise linear regulator is used to power the more noise sensitive components (gas sensor front end, humidity sensor).

Additionally, an ultra-low noise voltage reference can be optionally fitted to provide a stable voltage for the microcontroller ADC as well as the gas sensor analog front end.

	DC-DC (AOZ1280)	**Linear regulator (AP7361C)**	**Voltage reference (LM4120)**
Voltage accuracy	±2%	±1%	±0.2%
Line regulation	0.03% / V	0.01% / V	0.0007% / V
Load regulation	±0.5%	±1% (1A)	0.01% / mA
Noise	5mV (measured)	-	36uVpp

PSRR 1kHz	-	75dB	71dB

Table 4.9 Accuracy comparison of various voltage regulators in the design.

4.9.5 Capacitor Filtering and Selection

Generally electrolytic capacitors will be used to filter power supply switching noise. They have a self-resonant frequency of between 100kHz-1MHz. As our supply is operating at a much higher frequency (1.5MHz) it makes more sense to use ceramic capacitors. The self-resonant frequency of ceramics is in the range of 1MHz-1GHz.

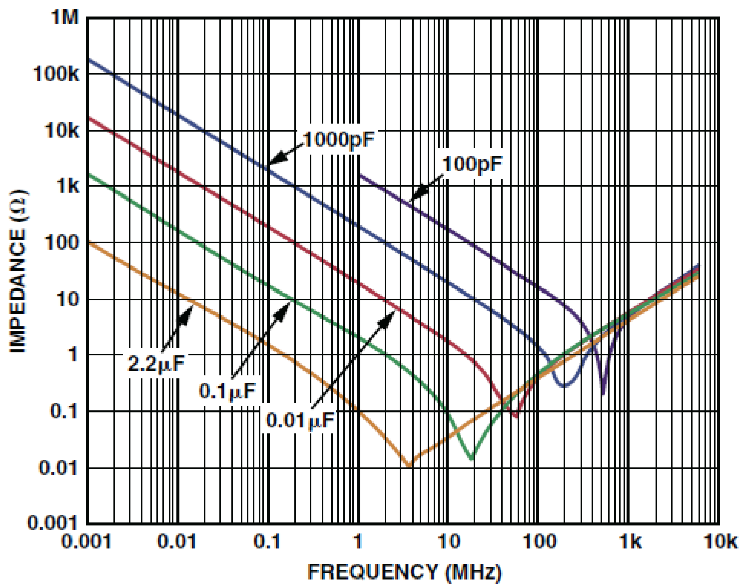


Fig. 4.21 Impedance vs. frequency of various capacitors [ARDI05].

The output filter capacitor chosen is 10uF which has SRF of approximately 1.8MHz, close to our switching frequency.

Derating at voltage

When selecting a ceramic capacitor, it is necessary to be aware of a number of properties. Change in temperature, as well as voltage, is significant. Depending on the material type (Y5V for example), capacitance could drop up to 80% at temperature extremes (-30°C or +80°C). For a device which will be used inside, this is not a concern as the capacitance is stable at room temperatures. When used outdoors however, the device could cease to function as expected.

Another property of ceramic capacitors is variation in capacitance with voltage. The closer your applied DC voltage is to the voltage rating of the capacitor, the lower its capacitance [FORT12]. For example, if a 4.7uF 6.3V X5R 0603 capacitor is biased with 5V, its capacitance will drop by over 60%. So, it's not as simple as choosing a capacitor with voltage overhead of say 20% for our circuit. To keep things simple, we can select a larger package size (0805 or 1206), which has less drop in capacitance.

4.9.6 Layout Considerations

PCB layout of the power supply is critical to meeting the specifications of the datasheet and will signify a good design. While connecting the various power components will result in a working power supply, if poor layout is implemented, noise may be high, and efficiency lower than expected. See PCB layout section for more information.

4.9.7 Backup/RTC Battery

Data will need to be stored in a non-volatile location to prevent loss during power outage. One method of storing this is EEPROM or Flash memory. STM32L4 supports writing to flash only, but it is a complex process. External EEPROM or Flash can be added, but will have limited write cycles and add BOM cost.

Another method is battery backed SRAM, a small section of memory in the microcontroller that stays powered using an external battery. Often this battery is Lithium based, but can also be a rechargeable type nickel metal (NiMH) or a capacitor. The amount of current consumption in the case of the STM32L4 is small, about 400nA for backup SRAM.

Timekeeping is useful to us in this application as it allows logging to provide a reference point (time of day). If an event occurs (high level of CO detected), the logs can be analyzed to pinpoint the exact second this occurred. In combination with other systems or security cameras for example, data can be compared to spot a source for the dangerous emission. The Real-time clock is another module that has very low operating current, and the ability to be always powered on.

Real-time clock current consumption on the STM32L4 is specified as 400nA, an incredibly low amount (leakage current of a CR2032 lithium cell is approximately 270nA). An external crystal is required to provide an accurate 32.768kHz clock to the RTC module.

	Lithium cell (CR2032)	**Super capacitor (0.1F)**	**NiMH cell (40mAH)**
Price	$0.26	$1.00	$1.50
Capacity	22 mWh	0.3 mWh	140 mWh
Life (given 400nA draw)	64 years	10 days	11 years
Charging cycles	none	∞	~500
Operating temperature	-30 to 80°C	-25 to 70°C	0 to 40°C

Table 4.10 Performance comparison of battery technologies [MAXI06].

An electric double layer capacitor (super capacitor) was chosen as the power source for backup SRAM and RTC data. In most commercial cases the lithium cell would be the best choice for this application. However, capacitor was chosen out of personal interest.

Capacity of a capacitor can be measured as follows:

a) Capacitor charged 2.08V in 18s with constant current source 10.5mA
b) C = i (dt/dV) = 10.5mA * (18s/2.08V) = 0.091 F

5 SOFTWARE DESIGN

5.1 Software Development Environment

Comparison of development environment for STM32 processors. Other options are available but are not discussed due to cost or popularity (e.g. IAR).

	System Workbench	Atollic	VisualGDB
Cost (CAD)	$0	$0 to $78/month	$57/1yr*
IDE	Eclipse	Eclipse (custom)	Visual Studio
Compiler	GCC C/C++	C/C++	GCC C/C++
Debug support hardware	ST-Link	ST-Link, J-Link	ST-Link, J-Link
Debug feature	Live variable	Live variable, visual watch, profiling, RTOS	Live variable, visual watch
Autocomplete	Content assist	Content assist	Intellisense
Forum posts	700	440	2,634
RTOS support	User supported	embOS, FreeRTOS, etc.	FreeRTOS
Static code analysis	No	Yes	No

Table 5.1 Software development environment comparison.

**After 50% educational discount*

Starting with System Workbench, it has the advantage of being completely open source and free. While System Workbench does not appear to have much activity based off forum posts, it is much bigger than it seems. The project is really a “pre-assembled” setup of Eclipse and a number of GNU ARM plugins. Many individuals will setup their own configuration based on these tools, for customization or other reasons. This alternate setup is not discussed here for time reasons, a simple, ready to go IDE is what is preferred.

Atollic is also based on the Eclipse IDE, but is commercially backed. Licensing cost is per month for the pro version. While Atollic is the most powerful development package, many of the advanced features are not available in the free version and require a payment of $59/month. If development is expected to last for about 6 months this is a total cost of $470, a significant portion of the project cost.

VisualGDB is a plugin for the free version of Visual Studio, a popular IDE developed by Microsoft. Visual Studio is incredibly refined and available for free via the Community edition.

All three packages have ready to go example projects, allowing easy to get going project such and blinking an LED.

5.2 Software Design Tools

STM32CubeMX

STM32CubeMX is a graphical tool to ease the setup of ST microcontrollers. Modern microcontrollers have complex startup procedures and a large number of registers. For example, the STM32L476 reference manual has 1693 pages, detailing steps and calculations for setting up various peripherals and core registers. Having software to simplify the selection of pin states and peripherals is certainly appreciated and will reduce the chance of making erroneous configurations (setting an unsupported PLL multiplier for example).

The software is setup using three main components: pinout, clock, and peripheral configuration.
First pinout selection is performed. Pins for required oscillators are designated first, next are our necessary peripherals (UART and I^2C). Finally, general purpose I/O pins can be chosen (LED status lights and switch inputs) from the remaining unassigned pins.

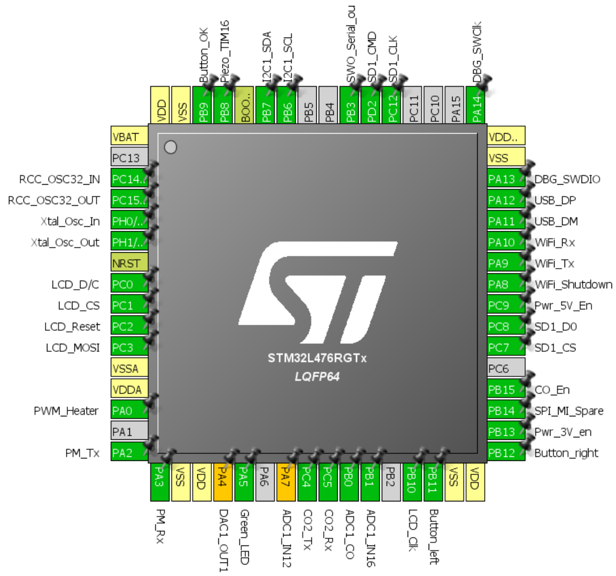


Fig. 5.1 Pinout configuration page

For example, pin PC4 can be an analog pin, GPIO input, output, or USART Tx pin. In this case, we select Tx pin as we will need it for communicating with the CO_2 sensor.

Next clock sources and PLL multipliers are selected. An external 32.768kHz crystal is used for timekeeping so we select that. An internal 4MHz clock is multiplied by 40, divided by 2, to form the 80MHz system clock. Various other multipliers and divisors are selected so peripherals will receive appropriate clock rates (not too high). USB for example must be clocked exactly at 48MHz.

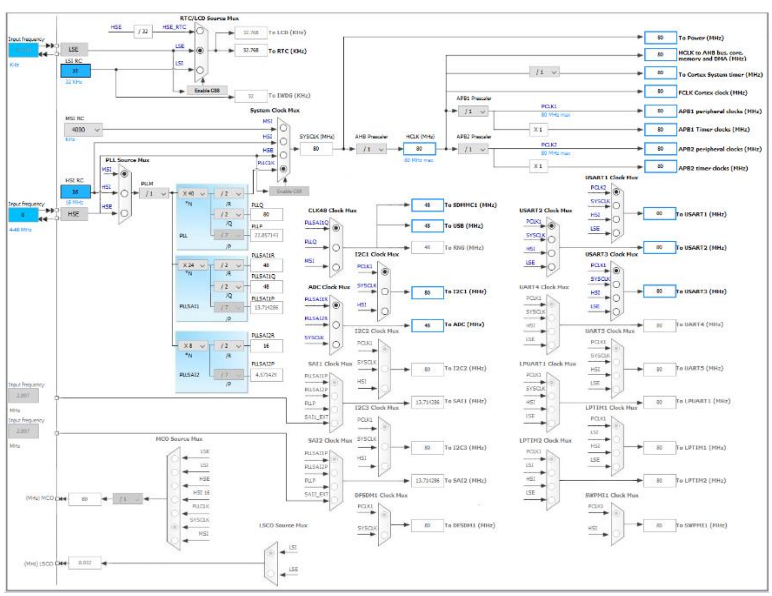


Fig. 5.2 Selection of main and peripheral clocks

Peripheral configuration is next, each peripheral has a number of settings to choose. I^{2}C, SDMMC, SPI, USART, USB, ADC, RTC, and timers. The example image below shows our I^{2}C port is programmed for a 100kHz speed, and 7-bit address length, among other options.

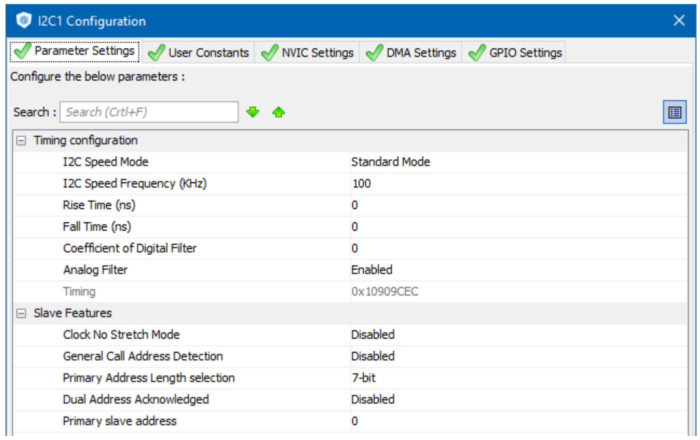


Fig. 5.3. Peripheral configuration page for I2C.

6 EXPERIMENTAL WORK

6.1 Measurement of Carbon Dioxide in an enclosed room

The Air Quality Monitor was placed in a bedroom and left running overnight to monitor carbon dioxide levels. The room was 2.4x2.5x3.9 meters in size (volume of 23.4m^3). One person was sleeping during this time. The door was closed and ventilation (air vent) was blocked off. However, some air would still be able to enter/exit the room via space below the door and gaps in windows. Measurements were taken overnight, and the relevant 5-hour period was graphed and is shown below.

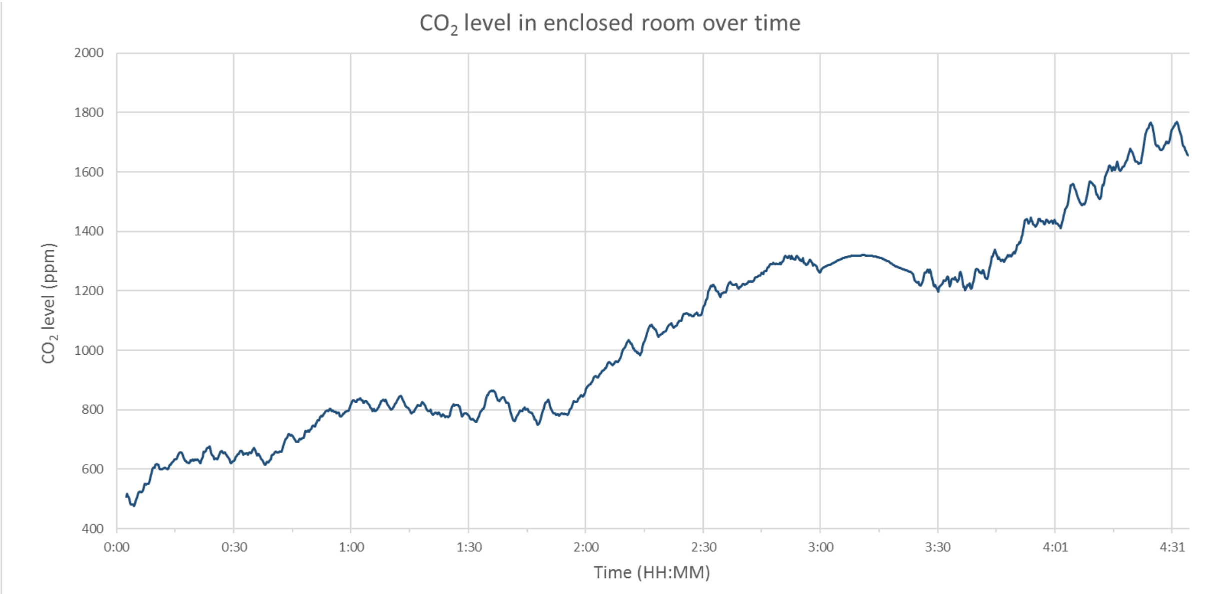


Fig. 6.1 CO_2 level in an enclosed room over time.

Dips in CO_2 are seen at 1hr and 3hr, and are due to the door being opened. The fastest increase in levels occurs at 2hr mark, and slope is 746ppm/hr. To convert this to m^3/h:

$$746 \text{ ppm} = 0.0746\%$$

$$23.4 \text{ m}^3 * 0.0746\% = 0.0175 \text{ m}^3$$

The reference level is 0.013m^3/h for sleeping [TETB17], close to what was measured. If we consider working being from 0.02 to 0.13m^3/h, this would give us a ppm/h increase in an average office (17.3 m^3) of 1,156 to 7,500 ppm/h.

This is a cause for concern if ventilation is not working properly and an employee is in a closed office. Levels could quickly build up to the point of decreased mental performance, and show importance of a low-cost air quality measurement system.

6.2 Measurement of air quality when soldering

Soldering is a common task performed when designing electronics or when manufacturing. While it is commonly known that good ventilation and filtering is recommended for soldering, the precise level of ventilation and its effect on air quality is not generally discussed. Some may recommend pointing a small fan at what is being soldered to blow smoke away, others will say proper extraction and filtering with an activated carbon filter is necessary.

A test using three techniques for air filtration will be performed:

a) No fan

b) Fan pointing at soldering iron (no filter)
c) Fan pointing away from soldering iron (carbon filter)

Testing was performed in a small 24m^3 room with typical forced air ventilation. The AQM was placed 25cm above the desk where soldering was taking place, to approximate location of breath intake.

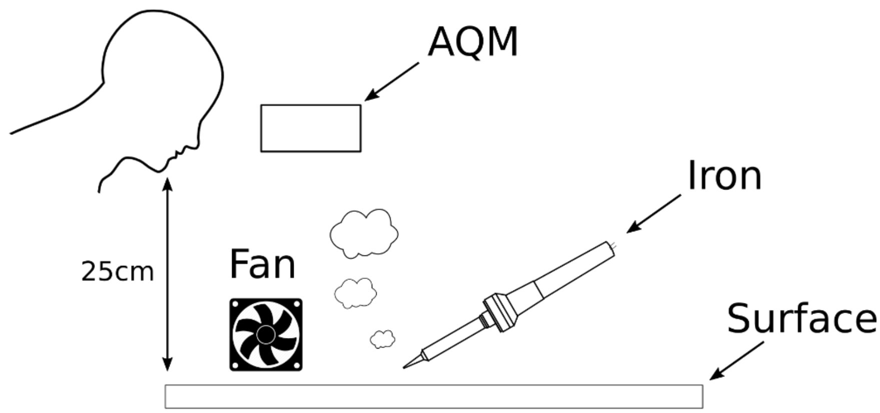


Fig. 6.2 Side view of soldering experiment

For the tests with a fan, it was placed 15cm off to the left of the board being soldered.

Note that while the fan is rated up to 131 m^3/h (77 CFM), with the filter attached the airflow will be greatly reduced due to restriction from the carbon filter.

Soldering tests were performed as follows:

- Air Quality Monitor is powered on and left for 1 hour for sensors to stabilize, and for baseline readings to be established
- Soldering iron turned on and wait 10 minutes to ensure its temperature has stabilized
- Clean tip thoroughly on brass shavings
- Solder 10 through hole joints in the span of 1 minute using 20cm of solder
- Wait 5 minutes
- Turn off soldering iron

Equipment used:

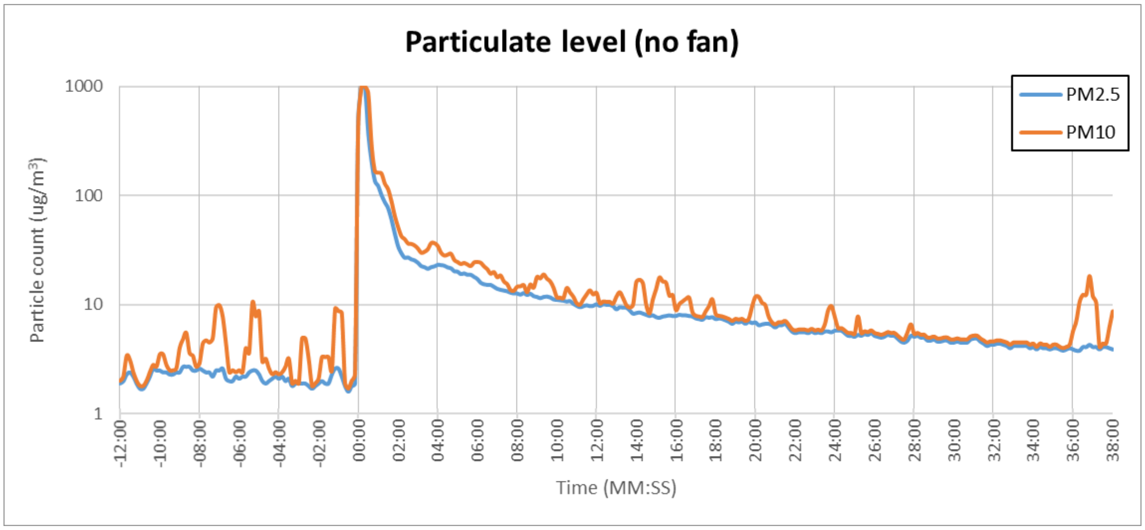
- Soldering station (Metcal PS2E-01)
- Soldering tip A (STTC-037 357 °C)
- Soldering tip B (STTC-137 412 °C)
- Rosin core solder (SRW6337060-0500)

- 63% tin, 37% lead
- 183 °C melting point

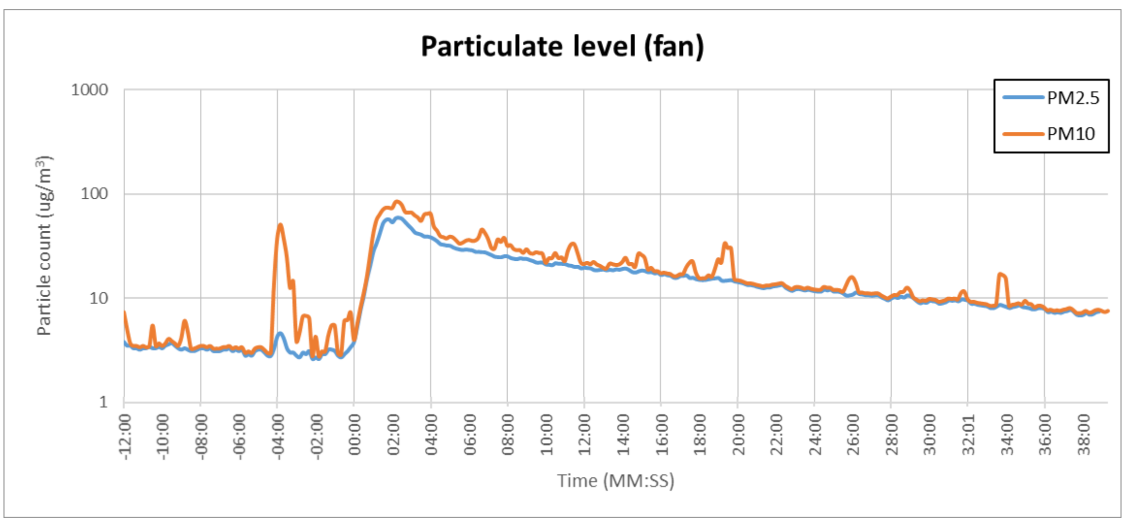
- Lead-free rosin core solder (Bow SAC305)
  - 96.5% tin, 3.0% silver, 0.5% copper
  - 220 °C melting point
- 120x25mm 77 CFM fan (FA12025M12SPA)
- Activated carbon filter, 9g (WSA350F)

6.2.1 Particulate Results

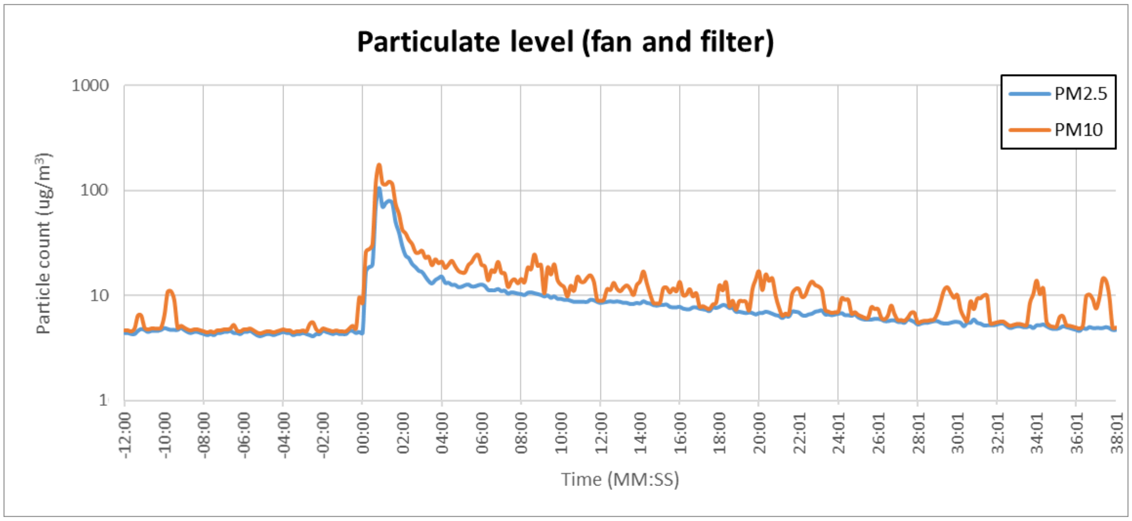
A) No fan results



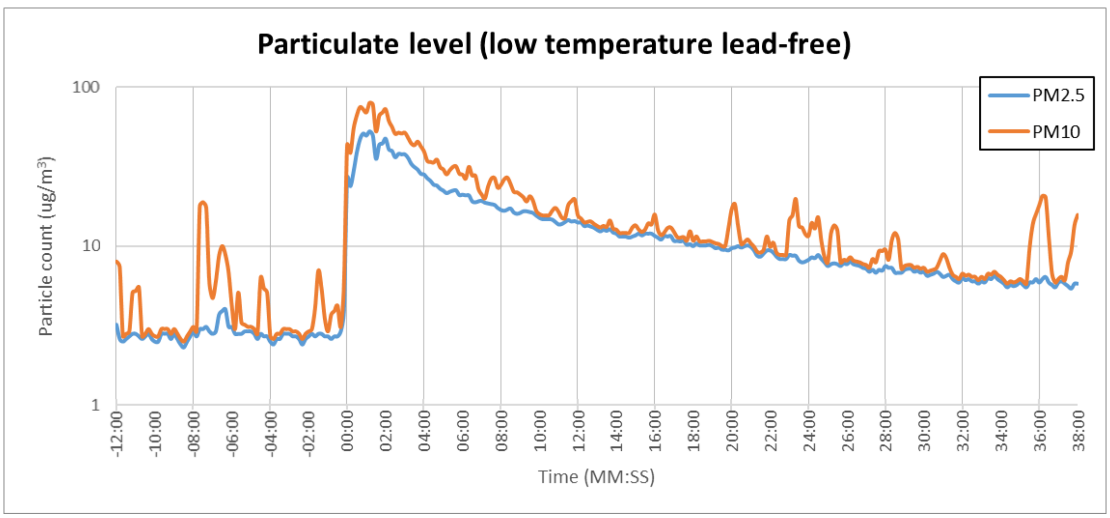
B) Fan without filter results

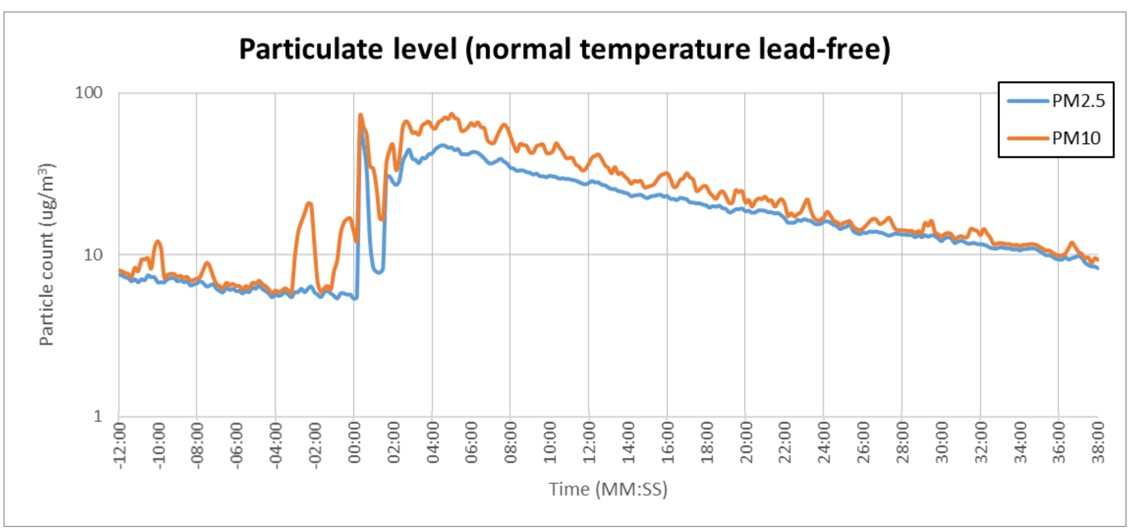


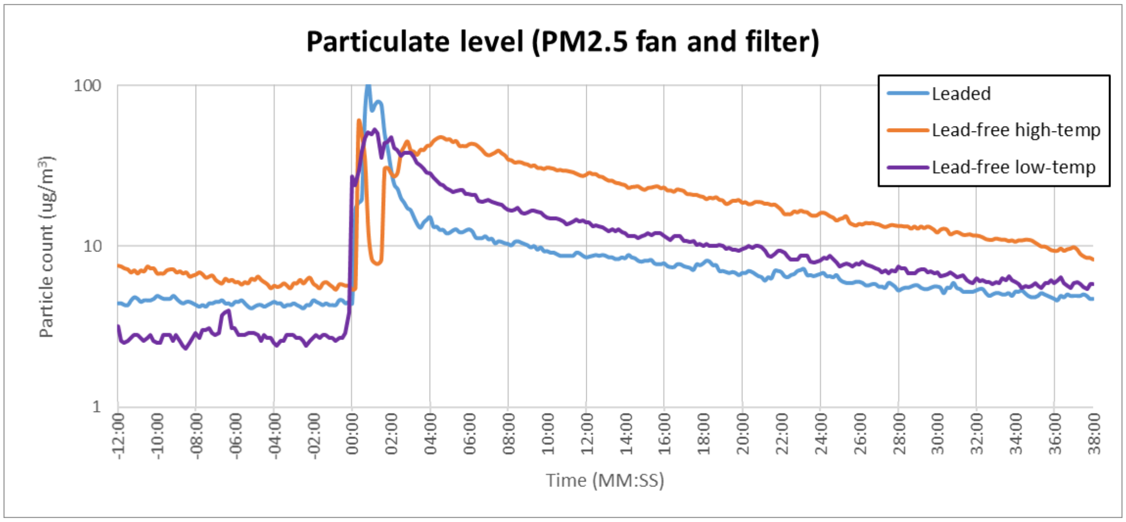
C) Fan with filter results



Lead-free comparison



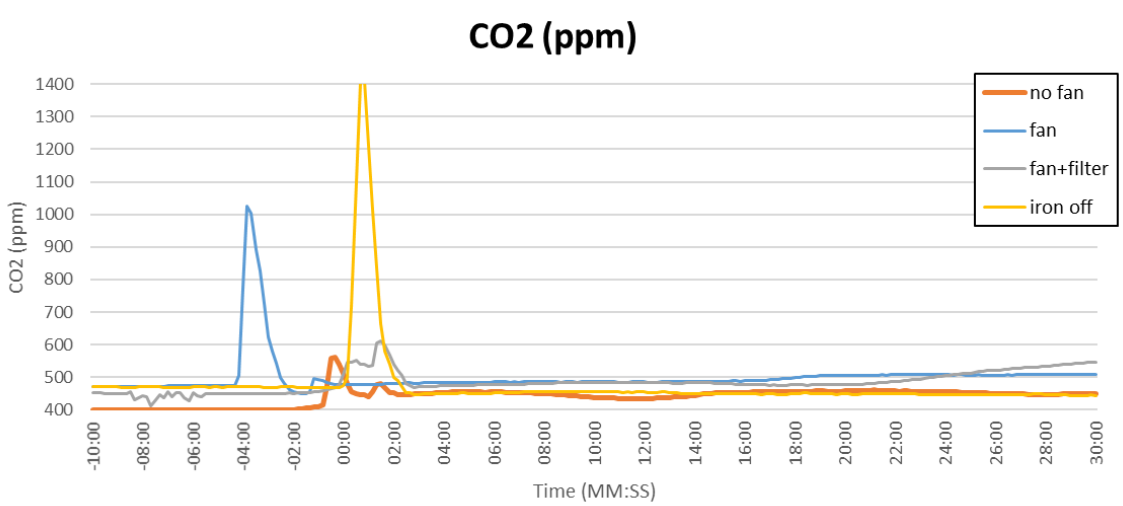




What is seen is a greater increase in particulate count with a higher iron temperature. The actual solder (lead or lead-free) does make a difference as well, but not as great. Most likely this is due to the rosin composition. Lead-free solder will have a slightly different rosin make-up to compensate for its increased wetting time.

6.2.2 Carbon Dioxide results

Carbon dioxide was measured on the AQM at the same time as particulate matter.



No significant change in carbon dioxide is seen depending on soldering filtering method. This is expected as soldering is not warm enough to cause any significant combustion (357 °C maximum in this case). A peak in CO_2 is visible when soldering, as the position of the AQM is right beside my mouth, so exhaled air has high levels of CO_2 in that area. If the AQM was placed further away, air would be suitably mixed and no peak in CO_2 is seen. After completing the soldering, I move away from the AQM, so levels drop back to what they were prior to the experiment (~450ppm).

6.3 Portable measurement during commute

A simple battery pack was built using two lithium-ion cells (18650 type). Output voltage of the two series cells is between 7 to 8.4V which is enough to supply the AQM. Each cell has a rating of 2600mAh which would give an operating time of over 11 hours, more than enough to measure exposure during a commute.

Fig. 6.3. Battery pack for AQM

Fig. 6.4. Battery pack shown powering the AQM

The AQM was carried during a commute to work in the morning. First using transit (walking, bus, and SkyTrain) and second was driving. Location was logged using an Android phone and the application "GPSLogger". In the future location data can be correlated with measurement data to provide a 3d map of "hot spots" to be avoided.

6.3.1 Commuting via Transit

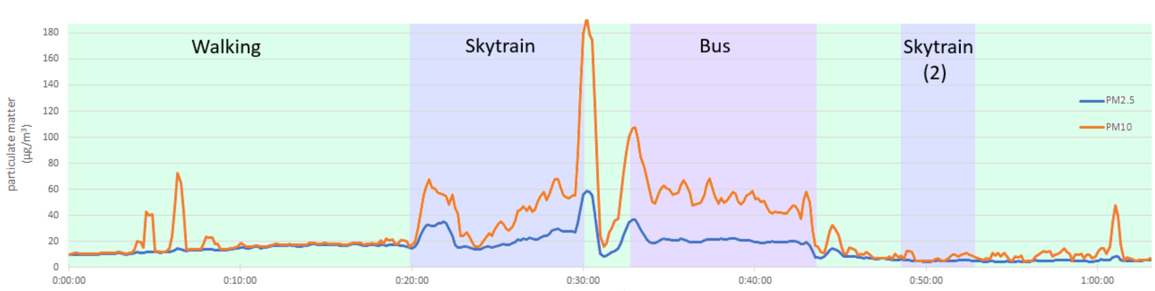


Fig. 6.5. Particulate levels during morning commute via transit

The AQM must be exposed to surrounding air so was carried in an open mesh type bag when walking and on transit. The first 20 minutes are spent walking and a slight increase is seen from 100 to 200 μg/m^3 as I approach a busier main road. Levels increase drastically again once I enter the SkyTrain (#1). I speculate this is due to the large number of people moving around and the fact that the car is a restricted sealed space.

Additionally, the train is underground so it is harder to mix in fresh air from outside. CO_2 levels reinforce this as they are elevated underground, anywhere from 800 to 1000 ppm (a completely safe level but worth noting). Particulate levels drop then rise again once on the bus, since it was a cold day this bus is also sealed and relying mostly on recirculating air inside. SkyTrain #2 (above ground) is cleaner I believe due to lower number of people and the fact that it has access to fresh outside air.

6.3.2 Commuting via Bicycle

The AQM was attached to a backpack and measured data from two cycling routes. The first is commuting to work in the morning, on mainly side streets and bicycle routes. Very little traffic was present, and that shows in the particulate measurements.

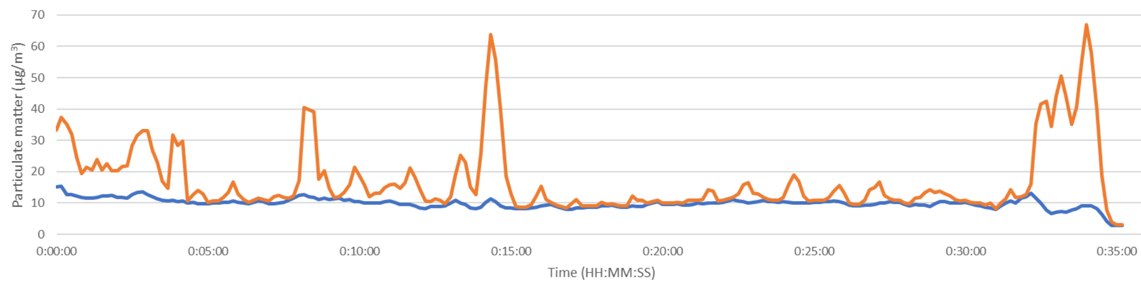


Fig. 6.6. Particulate exposure during cycling commute, low traffic.

At the 14 to 15-minute mark there is a small spike in particulate, this is from the crossing of a major street (Knight Street). Again, at the 32-minute mark, a similar spike is seen as I ride parallel to a four-lane road (Gilmore Ave.). Other than these peaks, the results are better than transit overall. However, if you did not have access to dedicated cycling roads or traffic calmed areas, results would be drastically worse. Riding on a major road puts you in the worst spot for exposure to poor air quality.

6.3.3 Commuting via Car

The levels of pollutants are elevated within 100m distance of most major roads (as seen on the right). This is very concerning as being in a vehicle would potentially put you within peak exposure of pollutants.

To investigate this, the AQM was placed on the passenger's seat in a vehicle during a typical morning commute. The climate control was set to

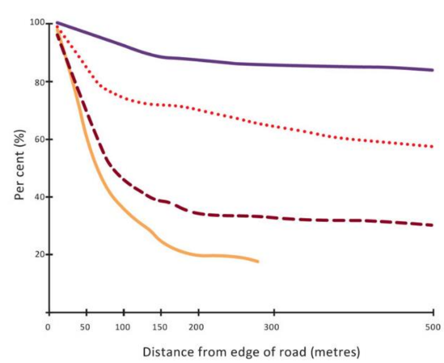


Fig. 6.7 Relative concentration of air pollutants near roadway [KARN10].

intake fresh air from outside and the windows were closed. As seen below, it appears that the cabin air filter within the car is doing a very good job of filtering most of these particulates out.

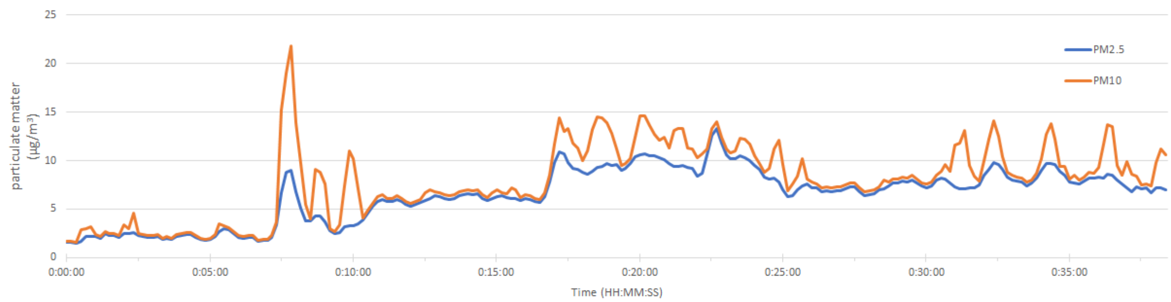


Fig. 6.8. Particulate exposure during vehicle commute, filtered air

The next experiment used the recirculation function of the climate control, which cycles air within the cabin. Having the fan off would have a similar effect, if the windows are kept closed.

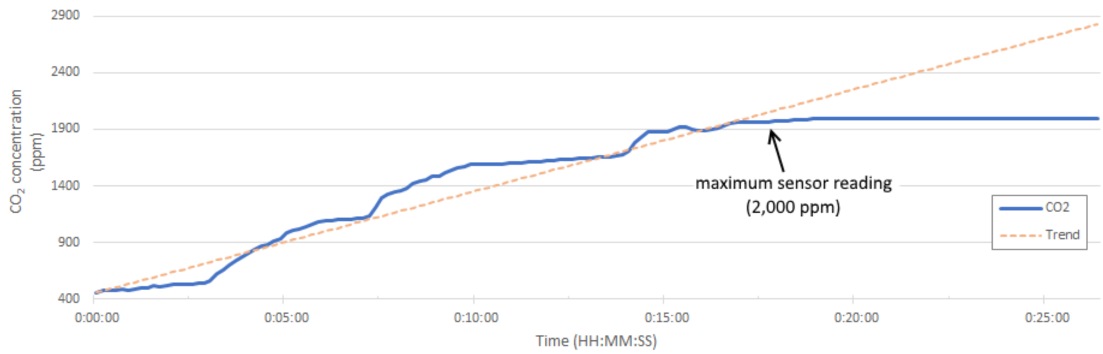


Fig. 6.9 Level of CO_2 within car when using recirculation mode.

It is seen in Fig. 6.9 that recirculation will cause CO_2 levels to build up as stale air is kept inside the vehicle. The sensor topped out at 2,000 ppm but would have kept rising to reach approximately 3,000 ppm after 30 minutes of driving. To avoid diminished mental performance, I would recommend opening the car window every 15 minutes or so to cycle in fresh air. Or better yet using the fresh air intake for most optimal levels.

7 CONCLUSIONS

From measurements and calculations in 6.1 (Measurement of Carbon Dioxide in an enclosed room), it is clear that dangerous levels of CO_2 can build up quickly in a small office. Typical offices will not have any way of sensing air quality let alone responding to the bad air quality occurrence. The same applies to a car cabin, where mental performance is arguably even more important.

From the measurements in 6.2 (Measurement of air quality when soldering) we see that ventilation is very important for soldering and avoiding health risks of particulate matter. A good fan with carbon filter should be used, and should be left on for 30 minutes after soldering, it should not be turned off immediately after.

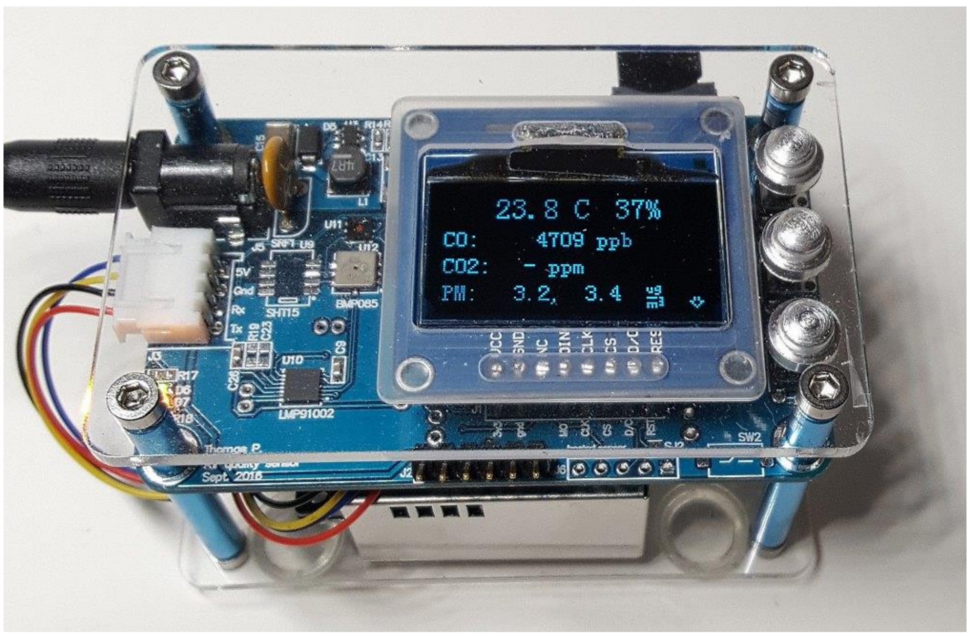


Fig. 7.1 Completed Air Quality Monitor.

The AQM design and software forms a useful tool for live monitoring of air quality as well as auditing environmental changes. Exposure over a long period of time can also be tracked if the device is powered via battery and carried by the user.

The final build cost of $168 for parts plus labor would result in a commercial product that is affordable enough for office use and even for the home of those that care about air quality and its relations to their health.

8 PROPOSALS FOR FURTHER WORK

8.1 Additional Sensors

Using my reference design, additional sensors could be attached for measuring risk gases I have not tested. For example, in NASA’s clean air study, they measured a number of VOCs such as benzene, formaldehyde, trichloroethylene, xylene, and ammonia.

8.2 Improved CO Sensor Resolution

I have used analog front end (AFE) for the carbon monoxide sensor, feeding into the ADC within the microcontroller for simplicity. With the integrated 10-bit ADC this gives a suitable value for detecting extremely hazardous conditions (800 ppm will result in death within 2-3 hours). However, for air quality monitoring, typical levels are much lower (less than 4 ppm) and much more resolution is needed.

As is seen from the Air Quality Egg (2.1.1), a ppb (parts per billion) reading is used. While I can’t comment on the accuracy of this reading (MiCS sensor datasheet specifies the minimum CO detecting range as 1 ppm and eggs come uncalibrated), it would still be a useful goal. In my case, it may be possible to get much greater actual resolution, and the sensor is pre-calibrated so can be trusted.

To improve this the AFE could be replaced with a lower noise hand designed transimpedance amplifier circuit, at the cost of increased board space and higher cost. Additionally, a higher resolution/lower noise external ADC can be used to read the amplifier output (Microchip MCP3422 18-bit ADC for example).

8.3 Portable Measurement

Stationary testing is only the beginning. Currently I used an Android phone to monitor position information, but my design could be expanded by adding a GPS module to simplify location logging. These time stamps and location data can be correlated with the AQM sensor readings, giving a map of air quality in certain areas. For example, one could mount the AQM to a backpack and while walk around industrial or commercial areas. An external battery would need to be used, but it would not have to be very large. From my calculations three rechargeable 18650 lithium cells (18mm x 65mm each) would power the AQM for more than a day.

Logged data would be processed later, on a PC, and any spikes could be investigated. For example, re-visiting the site and performing stationary measurements. Unusual readings could be reported to the city or to business owners to investigate the cause of poor air quality in that area.

8.4 More Soldering Tests

I have only tested a few methods of solder fume extraction and filtering. Varying fan speed, filter material, and fan location are all viable options for reducing exposure to particulate matter. Additionally, tests can be performed with lead-free solder and hotter lead-free capable soldering tips. It is likely the higher temperatures will produce much greater number and more hazardous smoke particles. It is widely argued that the move to lead-free may not be so environmentally clear cut as it was imagined to be.

8.5 Online Visualization of Data

It is convenient and helpful to display the air quality monitor data online. This allows comparison with other local readings as well as remote monitoring from a phone or PC. While the ESP8266 is integrated into the design for web access, it is still a work in progress. Work needs to be done to send the data to a monitoring server and produce graphs over time or location. The server could allow collaboration with other users, similar to how the Air Quality Egg server operates. An example platforms can be found here: https://emoncms.org/

9 REFERENCES

[APCI17] Air Products and Chemicals Inc, "Dangers of oxygen-deficient atmospheres. Effects of oxygen-deficient atmospheres," 2004. [Online]. Available: http://www.airproducts.com/~/media/files/pdf/company/safetygram-17.pdf. [Accessed: 28-Mar-2017].

[ALLA13] T. Allan, "De-construction of the Shinyei PPD42NS dust sensor." 2013.

[ARDI05] J. Ardizzoni, "A Practical Guide to High-Speed Printed-Circuit-Board Layout," *Analog Dialogue*, 2005.

[ARUN86] A. V Arundel, E. M. Sterling, J. H. Biggin, and T. D. Sterling, "Indirect health effects of relative humidity in indoor environments.," *Environ. Health Perspect.*, vol. 65, pp. 351–61, Mar. 1986.

[BAIL17] A. Bailes, "A UL-Listed Carbon Monoxide Alarm May Not Protect You." [Online]. Available: http://www.greenbuildingadvisor.com/blogs/dept/building-science/ul-listed-carbon-monoxide-alarm-may-not-protect-you. [Accessed: 08-Apr-2017].

[BUDD12] M. Budde, M. Busse, and M. Beigl, "Investigating the use of commodity dust sensors for the embedded measurement of particulate matter," *2012 Ninth Int. Conf. Networked Sens. Syst.*, pp. 1–4, 2012.

[CCME00] Canadian Council of Ministers of the Environment, *Canada-wide standards for particulate matter and ozone*. Canada, 2000.

[CESA14] G. Cesaroni *et al.*, "Long term exposure to ambient air pollution and incidence of acute coronary events: prospective cohort study and meta-analysis in 11 European cohorts from the ESCAPE Project.," *BMJ*, vol. 348, no. 2, p. f7412, Jan. 2014.

[CHAN13] N. Chantrell, "Air Quality Egg – Community air quality monitoring," 2013. [Online]. Available: https://nathan.chantrell.net/20130210/air-quality-egg-community-air-quality-monitoring/. [Accessed: 08-Apr-2017].

[DIAM10] Diamond Environmental Ltd., "Particulate pollution – PM10 and PM2.5 | Recognition, Evaluation, Control," 2010. [Online]. Available: https://diamondenv.wordpress.com/2010/12/10/particulate-pollution-pm10-and-pm2-5/. [Accessed: 12-Mar-2017].

[EWG14] Environmental Working Group, "Health Concerns for Silica in Outdoor Air," 2014. [Online]. Available: http://www.ewg.org/research/sandstorm/health-concerns-silica-outdoor-air. [Accessed: 28-Mar-2017].

[FORT12] M. Fortunato, "Temperature and Voltage Variation of Ceramic Capacitors," *Maxim App Note*, 2012. [Online]. Available:

https://www.maximintegrated.com/en/app-notes/index.mvp/id/5527. [Accessed: 28-Mar-2017].

[GEAR16] Gearbest, “Xiaomi Smart Air Quality Monitor PM2.5 Detector,” 2016. [Online]. Available: http://www.gearbest.com/living-appliances/pp_557543.html. [Accessed: 08-Apr-2017].

[GOVI16] R. Govindjee, “What is photosynthesis?” [Online]. Available: http://www.life.illinois.edu/govindjee/whatisit.htm. [Accessed: 01-Dec-2016].

[GREN01] L. M. Grenci and J. M. Nese, *A World of Weather: Fundamentals of Meteorology: A Text/ Laboratory Manual*. Kendall/Hunt Publishing Co, 2001.

[HÄGG14] M. Häggström, “Medical gallery of Mikael Häggström 2014,” *WikiJournal Med.*, vol. 1, no. 2, 2014.

[HOLS14] D. M. Holstius, A. Pillarisetti, K. R. Smith, and E. Seto, “Field calibrations of a low-cost aerosol sensor Field calibrations of a low-cost aerosol sensor at a regulatory monitoring site in California Field calibrations of a low-cost aerosol sensor,” *AMTD Atmos. Meas. Tech. Discuss*, vol. 7, no. 7, pp. 605–632, 2014.

[HUAN10] A. Huang, “On MicroSD Problems,” 2010. [Online]. Available: http://www.bunniestudios.com/blog/?p=918. [Accessed: 03-Apr-2017].

[ILT17] International Light Technologies, “NDIR Gas Sensor Light Sources.” [Online]. Available: https://www.intl-lighttech.com/applications/light-sources/ndir-gas-sensor-lamps. [Accessed: 03-Apr-2017].

[IST05] International Sensor Technology, “Electrochemical Sensors,” 2005. [Online]. Available: http://www.intlsensor.com/pdf/electrochemical.pdf. [Accessed: 03-Apr-2017].

[JDVA12] A. J.D. van Wyk, M. Visser, and D.B. Rademeyer, “A standards-based approach to capacitive sensor EMC problems,” *Embedded.com*, 2012. [Online]. Available: http://www.embedded.com/print/4370445. [Accessed: 28-Mar-2017].

[KARN10] A. A. Karner, D. S. Eisinger, and D. A. Niemeier, “Near-Roadway Air Quality: Synthesizing the Findings from Real-World Data,” *Environ. Sci. Technol.*, vol. 44, no. 14, pp. 5334–5344, Jul. 2010.

[LU15] C.-Y. Lu, J.-M. Lin, Y.-Y. Chen, and Y.-C. Chen, “Building-Related Symptoms among Office Employees Associated with Indoor Carbon Dioxide and Total Volatile Organic Compounds,” *Int. J. Environ. Res. Public Health*, vol. 12, no. 6, pp. 5833–5845, May 2015.

[MAXI06] Maxim, “Selecting a Backup Source for Real-Time Clocks,” 2006. [Online]. Available: https://www.maximintegrated.com/en/app-notes/index.mvp/id/3816. [Accessed: 08-Apr-2017].

[MCMA09] N. Mcmanus, “Oxygen: Health Effects and Regulatory Limits Part I: Physiological and Toxicological Effects of Oxygen Deficiency and Enrichment,” North Vancouver, 2009.

[MEAD13] M. I. Mead *et al.*, “The use of electrochemical sensors for monitoring urban air quality in low-cost, high-density networks,” *Atmos. Environ.*, vol. 70, pp. 186–203, 2013.

[NAFI12] C. Nafis, “Monitoring your Air Quality,” 2012. [Online]. Available: http://www.howmuchsnow.com/arduino/airquality/. [Accessed: 03-Apr-2017].

[OU14] C. Q. Ou *et al.*, “The impact of relative humidity and atmospheric pressure on mortality in Guangzhou, China.,” *Biomed. Environ. Sci.*, vol. 27, no. 12, pp. 917–25, Dec. 2014.

[PARK08] E. J. Park, “Sensor Report - MQ3 Gas sensor,” 2008. [Online]. Available: http://sensorworkshop.blogspot.ca/2008/04/sensor-report-mq3-gas-sensor.html. [Accessed: 03-Apr-2017].

[PEAR11] C. Pearson, “Reading an SD card with an ATMEGA168,” 2011. [Online]. Available: http://elasticsheep.com/2010/01/reading-an-sd-card-with-an-atmega168/. [Accessed: 08-Apr-2017].

[REN06] C. Ren and S. Tong, “Temperature modifies the health effects of particulate matter in Brisbane, Australia,” *Int. J. Biometeorol.*, vol. 51, no. 2, pp. 87–96, Oct. 2006.

[SATI12] U. Satish *et al.*, “Is CO2 an Indoor Pollutant? Direct Effects of Low-to-Moderate CO2 Concentrations on Human Decision-Making Performance,” *Environ. Health Perspect.*, 2012.

[SEPP99] O. A. Seppanen, W. J. Fisk, and M. J. Mendell, “Association of Ventilation Rates and CO2 Concentrations with Health and Other Responses in Commercial and Institutional Buildings,” *Indoor Air*, vol. 9, no. 4, pp. 226–252, Dec. 1999.

[SEPP06] O. Seppänen, W. J. Fisk, and Q. Lei, “Effect of Temperature on Task Performance in Offfice Environment,” 2006.

[SEVE67] D. Sevel and A. Freedman, “Cerebro-retinal degeneration due to carbon dioxide poisoning.,” *Br. J. Ophthalmol.*, vol. 51, no. 7, pp. 475–82, Jul. 1967.

[SHEN14] C. Shen, “An Investigation of a Low-cost CO2 Indoor Air Quality Monitor,” no. May 2014, Jan. 2014.

[SMIT17] Dr. Linda Smith, “National Ambient Air Quality Standards for Particulate Matter.” [Online]. Available:

https://www.arb.ca.gov/research/aaqs/pm/pm.htm. [Accessed: 12-Mar-2017].

[TENG03] A. Tengberg *et al.*, “Optodes to Measure Oxygen in the Aquatic Environment,” *Sea Technol.*, 2003.

[TETB17] The Engineering ToolBox, “Carbon Dioxide Emission from People.” [Online]. Available: http://www.engineeringtoolbox.com/co2-persons-d_691.html. [Accessed: 28-Mar-2017].

[TOWN02] C. L. Townsend, “Effects on health of prolonged exposure to low concentrations of carbon monoxide,” *Occup. Environ. Med.*, vol. 59, no. 10, pp. 708–711, Oct. 2002.

[EIA16] U.S. Energy Information Administration (EIA), “Carbon dioxide emissions coefficients,” 2016. [Online]. Available: https://www.eia.gov/environment/emissions/co2_vol_mass.cfm. [Accessed: 08-Apr-2017].

[UCAR06] University Corporation for Atmospheric Research, “Carbon Dioxide,” 2006. [Online]. Available: https://scied.ucar.edu/carbon-dioxide. [Accessed: 28-Mar-2017].

[WOLK07] P. Wolkoff and S. K. Kjærgaard, “The dichotomy of relative humidity on indoor air quality,” *Environ. Int.*, vol. 33, no. 6, pp. 850–857, 2007.

[WONG16] C. M. Wong *et al.*, “Cancer Mortality Risks from Long-term Exposure to Ambient Fine Particle,” *Cancer Epidemiol. Biomarkers Prev.*, vol. 25, no. 5, pp. 839–845, May 2016.

[WOOD06] R. A. Wood, M. D. Burchett, R. Alquezar, R. L. Orwell, J. Tarran, and F. Torpy, “The Potted-Plant Microcosm Substantially Reduces Indoor Air VOC Pollution: I. Office Field-Study,” *Water. Air. Soil Pollut.*, vol. 175, no. 1–4, pp. 163–180, Aug. 2006.

[WAQ15] World Air Quality, “The Plantower PMS3003 Air Quality Sensor experiment,” 2015. [Online]. Available: http://aqicn.org/sensor/pms3003/. [Accessed: 03-Apr-2017].

[WHO06] World Health Organization, “Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide,” 2006.

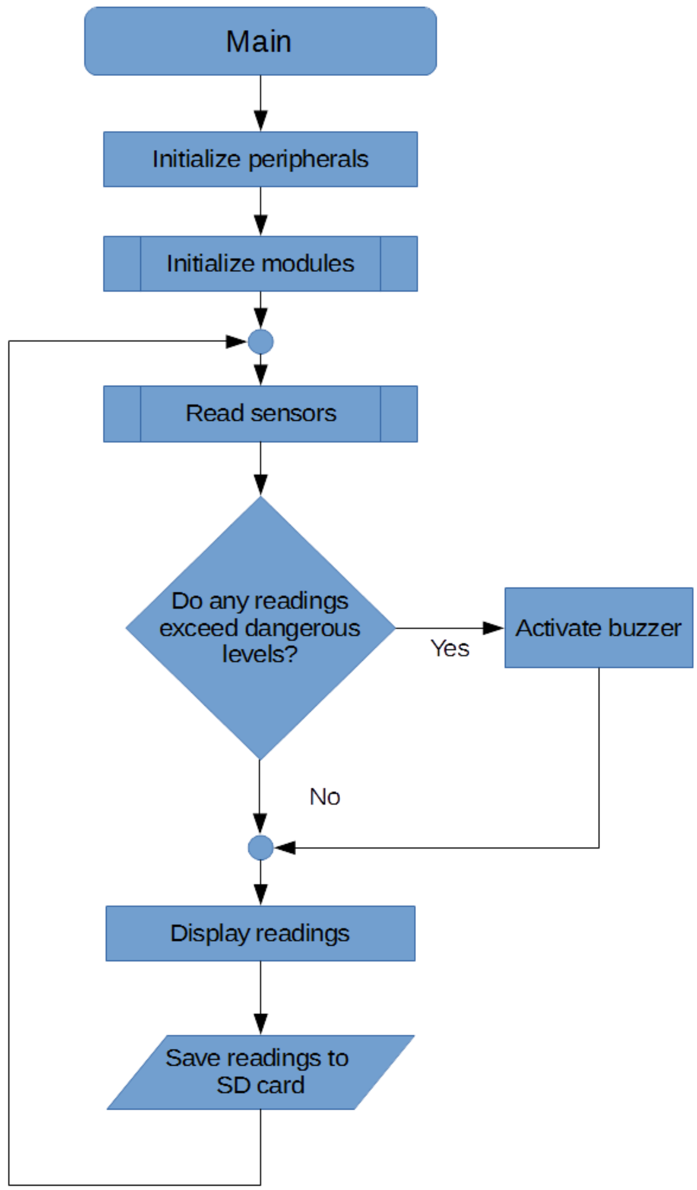
[ZAMP04] S. Zampolli *et al.*, “An electronic nose based on solid state sensor arrays for low-cost indoor air quality monitoring applications,” *Sensors Actuators B Chem.*, vol. 101, no. 1–2, pp. 39–46, Jun. 2004.

[ZEPT14] Zeptobars, “Espressif ESP8266 WiFi-serial interface,” 2014. [Online]. Available: https://zeptobars.com/en/read/Espressif-ESP8266-wifi-serial-rs232-ESP8089-IoT. [Accessed: 28-Mar-2017].

10 APPENDIX A: COMPUTER PROGRAM: FLOW CHART, REMARKS, & CODE

10.1 Flow Charts

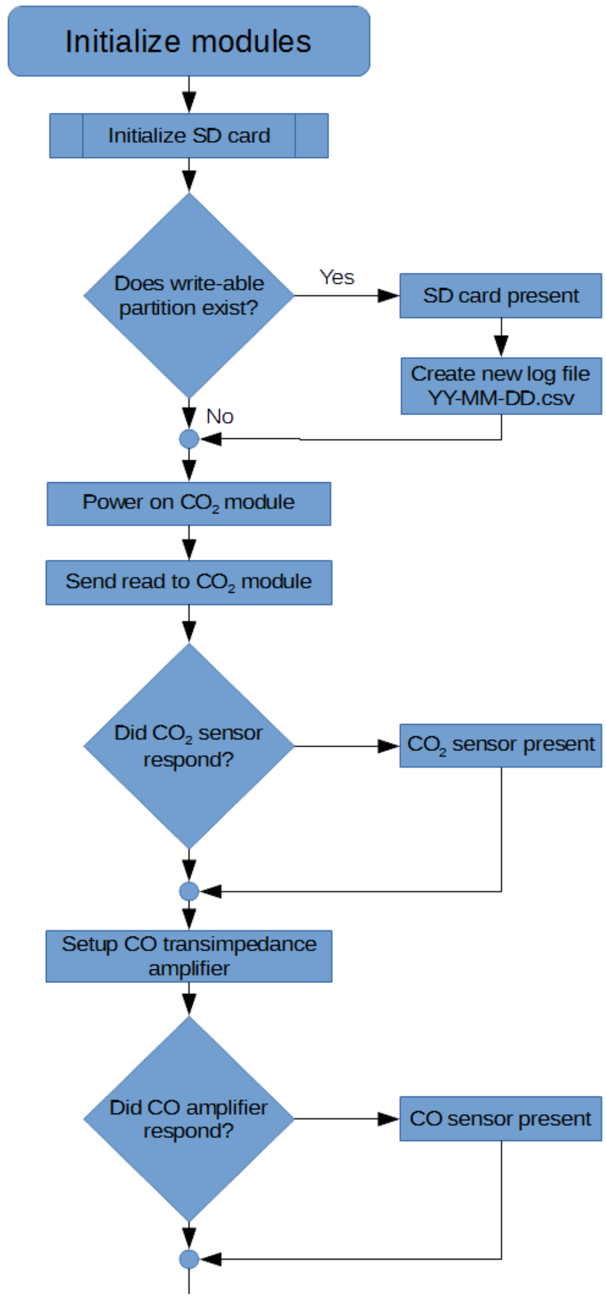
A) Main loop

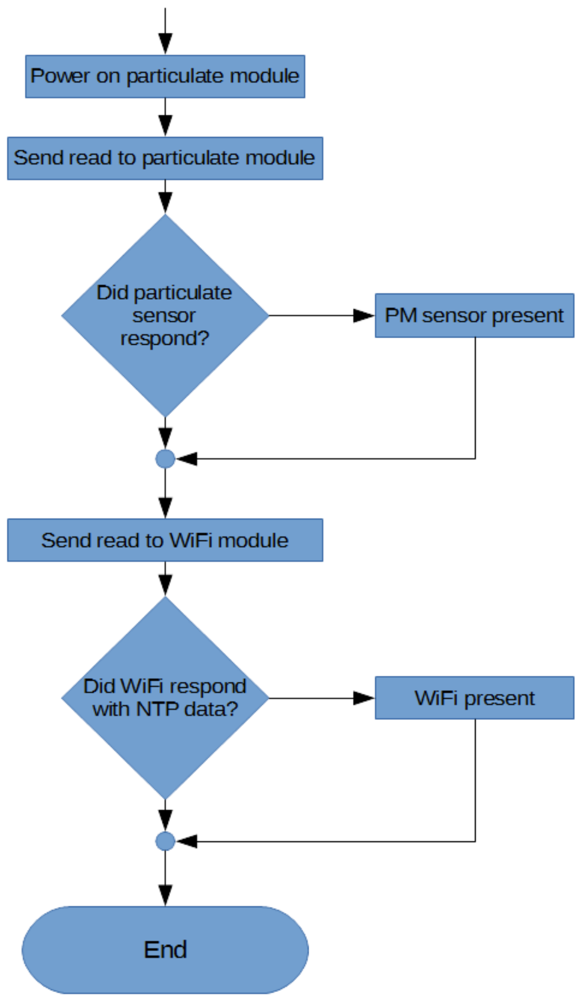


The main loop:

- Initializes internal aspects of the STM32L476 (gpio, timers, interrupts, etc.)
- Communicates with modules to determine if they are present (SD, WiFi, CO, PM sensors, etc.)
- If a sensor is present, it reads the value, and checks if this level is dangerous.
- When dangerous level is exceeded the buzzer will beep to alert the user
- Every reading update is then displayed to the user
- The data is also time-stamped and saved to the SD card

B) Initialization of modules




Power on particulate module
Send read to particulate module
Did particulate sensor respond?
PM sensor present
Send read to WiFi module
Did WiFi respond with NTP data?
WiFi present
End

10.2 SD memory card

SD cards are commonly connected to microcontrollers via SPI bus. However, the disadvantage is that not all cards support SPI mode, and speed of transfer is slower.

The chosen microcontroller contains both SPI and SDMMC peripherals, the SD card was connected to the SDMMC peripheral in 1-bit mode. 4-bit mode is available if higher transfer speed is required. However, for sensor logging 1-bit mode is more than enough, and SPI mode would work fine as well.

The SDMMC peripheral can operate up to 24MHz, in 1-bit mode this gives:

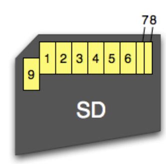
- 24MHz * 1-bit wide / 8-bit per byte = ~3MB/s

Physical connection:

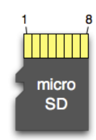
In the case of SPI mode, commands are sent to the card on DI pin (pin 3) and received on DO (pin 7). This requires a total of 4 data connections, three outputs and one input.

In 1-bit SD mode, only 3 data connections are needed. One output (clock), and two bi-directional connections (CMD and DAT0). When a command is sent on CMD, the SD card will respond on the same pin. This is similar to I^2C, but instead of open collector outputs and pullup resistors, the bidirectional lines are actively driven.

Communication initially occurs at a slow speed (400kHz or less) for compatibility reasons, and basic parameters are established (voltage range, card size, etc.). Then speed will later increase for higher throughput (25-50MHz).



Pin	SD	SPI
1	CD/DAT3	CS
2	CMD	DI
3	VSS1	VSS1
4	VDD	VDD
5	CLK	SCLK
6	VSS2	VSS2
7	DAT0	DO
8	DAT1	X
9	DAT2	X



Pin	SD	SPI
1	DAT2	X
2	CD/DAT3	CS
3	CMD	DI
4	VDD	VDD
5	CLK	SCLK
6	VSS	VSS
7	DAT0	DO
8	DAT1	X

Fig. 10.1. Pinout of a SD and MicroSD card for SD and SPI modes [PEAR11].

Initialization of card:

1. To initialize the card in SD mode, CS is pulled high and CMD0 is sent to reset all cards on the bus.
2. No response is expected.

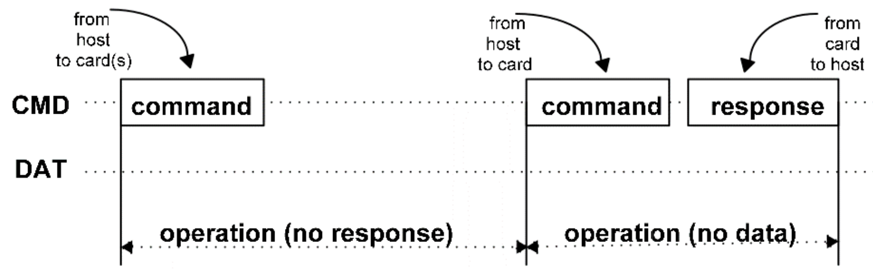


Fig. 10.2 Example of SD command with and without a response

3. Next CMD8 is sent, checking that the card will support the current voltage supply (3.3V = 0x01 in this case).

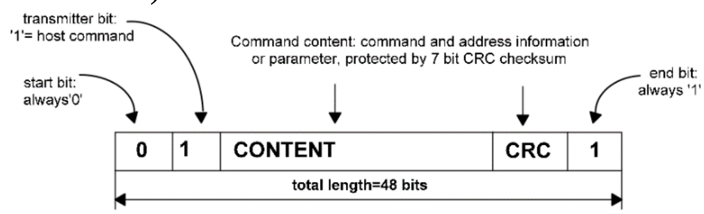


Fig. 10.3 Command packet format

4. The card responds with the same voltage (0x01) indicating support is present.

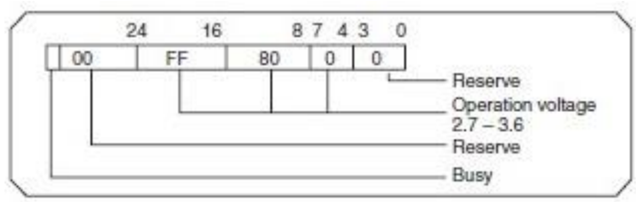


Fig. 10.4 R3 response containing operating voltage

5. CMD55 + ACMD41 are sent repeatedly until SD reports IDLE_STATE is left

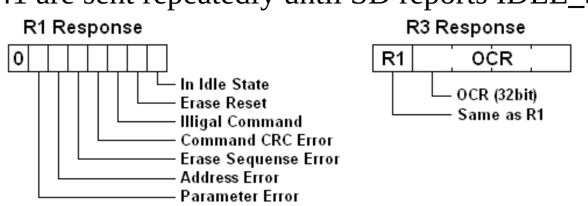


Fig. 10.5 R1 response indicating card state

6. Configuration of the card is then read (manufacturer ID, card size, block size, etc.)
7. Card now in standby state and data can be written/read

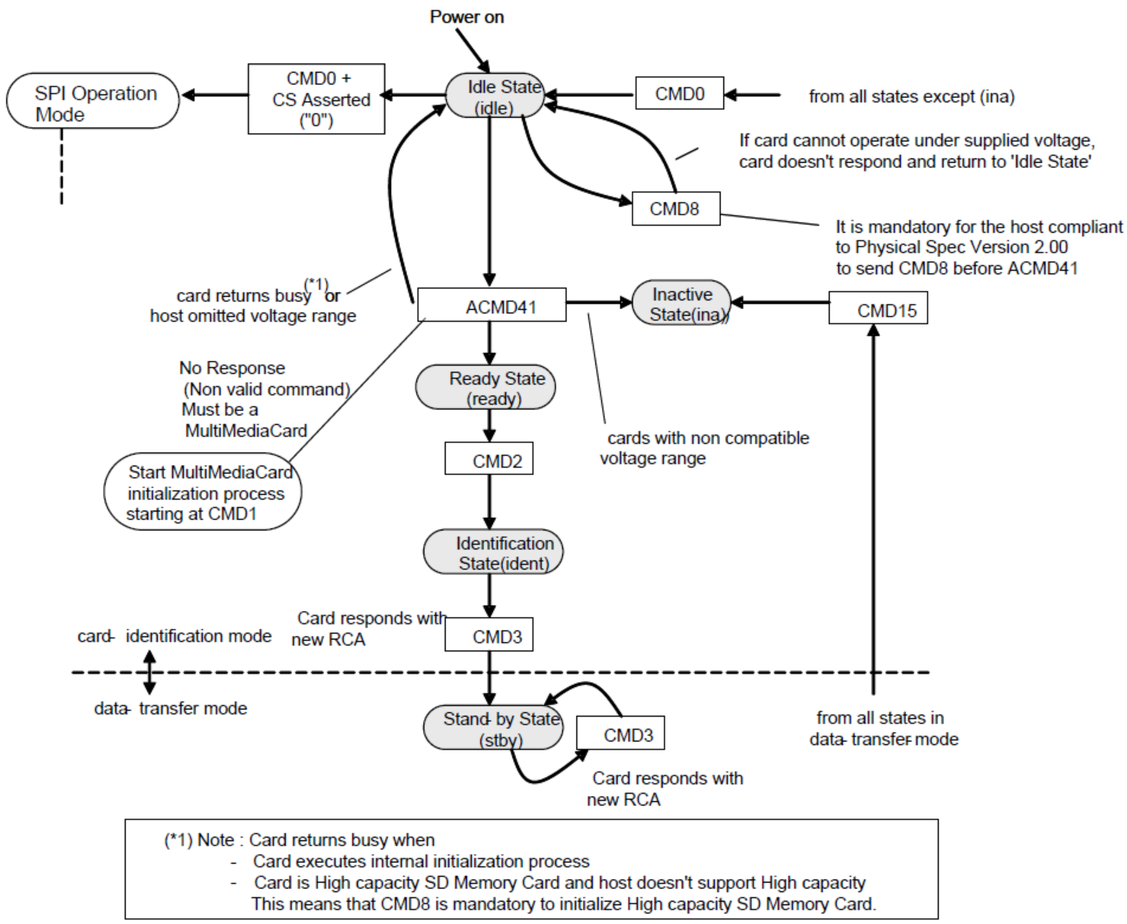


Fig. 10.6 State diagram of SD card communication

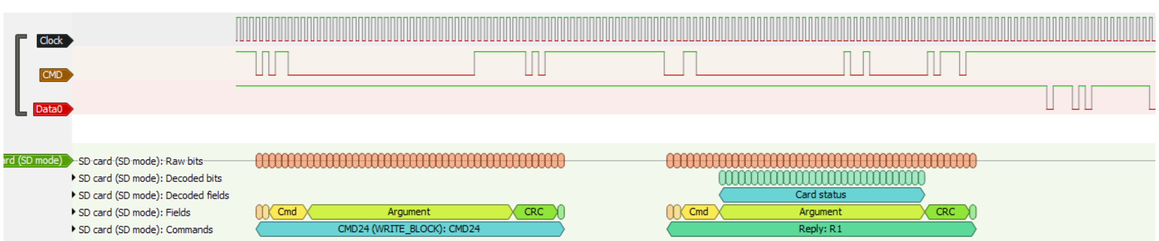


Fig. 10.7 Example SD data write, captured with logic analyzer

More information can be found in SD physical layer spec 2.0 (SD Group), September 2006.

10.3 Log analysis software (Excel)

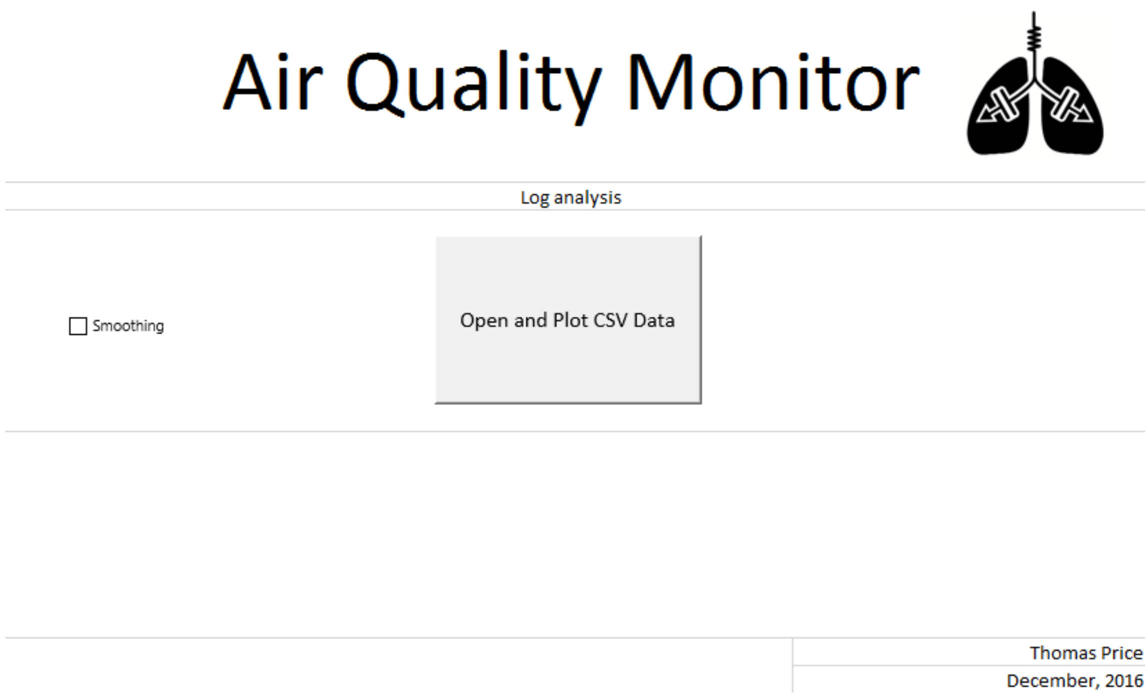
To simplify analyzing logs produced by the AQM, an Excel sheet was created to:

- Open the CSV file and import its data
- Create a sheet for graphs
- Graph the data vs. time for each sensor type

Format of CSV file is as follows:

```
Date,Time,Temperature (C),Humidity (%),Pressure (Pa),CO (ppm),CO2 (ppm),PM2.5,PM10,-,Status
2016-01-01,09:23:00,23.7,10,35342,006,128,035,047,
2016-01-01,09:23:05,23.7,10,35342,006,130,036,048,
…
```

Interface of tool:



Source code:

Source can be found by opening the included file: “AirQuality_Log_Plotter.xlsm”

10.4 Modules Listing

Main.cpp	Main application and peripheral setup.
BMP085_pressure.cpp	Pressure sensor driver
CO_110_Spec.cpp	CO_110 sensor data acquisition and processing/calibration
CO2_MHZ.cpp	MH-Z19 serial communication driver
ESP8266_wifi.cpp	Wireless module messages/driver
FF.c	FatFS filesystem driver
Graph.cpp	Graphing and storage of historical data
LMP91000.cpp	LMP91000 transimpedance amplifier driver
SD_card.cpp	CSV log structure and management of SD card data
SDS_PM_sensor.cpp	SDS021 particulate matter sensor serial driver
SI7020_humid.cpp	SI7020 humidity I2C driver
SSD1306.c	OLED display driver

10.5 Software Attributions

STM32L4xx HAL – Hardware abstraction drivers for STM32L4 by STMicroelectronics (2016)

FatFs – Generic FAT file system module by ChaN (2016)

BMP085 driver – pressure sensor driver by Limor Fried

SI7020 – humidity sensor driver by Maxim Integrated Products, Inc.

SSD1306 – OLED display driver by Waveshare Team (Oct 2014)

Excel tool – open a CSV file by Jon Peltier (2015)

10.6 Source Code

The full source code can be found here: https://gitlab.com/thmjpr/Air_Quality/

A few excerpts from main are copied below:

```
/**
********************************************************************************
  * @file    main.cpp
  * @author  Thomas Price
  * @version
  * @date    December, 2016
  * @brief   Main air quality application
  ******************************************************************************
  */

/* Includes ------------------------------------------------------------------*/
#include "main.h"
#include "error.h"
#include "sd_card.h"
#include "config_settings.h"
#include "graph.h"
#include "dma.h"
#include "usart.h"
#include "gpio.h"
#include "timer.h"
#include "rtc.h"
#include "adc.h"
#include "i2c.h"
#include "spi.h"
//#include "USB/usb_device.h"
#include "OLED/ssd1306_config.h"
#include "Hardware/BMP085_pressure.hpp"
#include "Hardware/si7020_humid.h"
#include "Hardware/LMP91000.h"
#include "Hardware/CO_110_Spec.h"
#include "Hardware/ESP8266_wifi.h"

//Volatiles
__IO bool new_sensor_read = false, new_SD_save = false, new_co2_read = false, new_day = false,
alarm_on = false, read_timer_ = false;
__IO KeyState key_status = Key_None;
__IO int32_t piezo_on_time = 0;

//---------------------------------------------------------------------------
//Sensor and communication objects
BMP085 bmp;
Si7020 humid;
SPEC_CO_110 co;
ESP8266 wifi(&huart1);
SDS_PM pm(&huart2);
CO2_MHZ co2(&huart3);
SD_CARD sd;
CONFIG cfg;

int co_level, co2_level;
float pm_level, pm_level_25;
menuScreens menu = mnuMain;

//===========================================================================
```

```
int main(void)
{
	char build_date[] = __DATE__;
	Graph grph;
	Graph::Graph_type graph_num = Graph::Temperature;
	SD_CARD::logData log;
	uint8_t num = 0, i, entering_settings = 0;
	bool key_ok_pressed = false;
	float ambient_temp, humidity, pressure;

	/* MCU Configuration----------------------------------------------------------*/
	/* Reset of all peripherals, Initializes the Flash interface and the Systick. */
	HAL_Init();

	/* Configure the system clock */
	SystemClock_Config();

	/* Initialize all configured peripherals */
	MX_GPIO_Init();
	MX_SPI2_Init();
	MX_DMA_Init();

	MX_USART1_Init();
	MX_USART2_Init();
	MX_USART3_Init(115200);
	//MX_USB_DEVICE_Init();
	MX_I2C1_Init();
	MX_ADC1_Init();

	MX_TIM1_Init();
	MX_TIM2_Init();
	MX_TIM16_Init();

	MX_RTC_Init();			//Configure real-time clock (base date is set)
	OLED_init();			//OLED initialization

	//-----------------------------------------------------
	srand(0x55);

	//Starting up
	ssd1306_rotate_screen(true);
	ssd1306_clear_screen(0);
	ssd1306_draw_bitmap(0, 0, &icon_splash_screen[0], 128, 64);		//Splash screen
	ssd1306_update();
	HAL_Delay(1900);
	ssd1306_clear_screen(0);

	//List modules available
	ssd1306_display_string(0, 0,   (uint8_t*)"SD card  ?", FONT_MED, 1);
	ssd1306_display_string(0, 15,  (uint8_t*)"Pressure ?", FONT_MED, 1);
	ssd1306_display_string(0, 30,  (uint8_t*)"Humidity ?", FONT_MED, 1);
	ssd1306_display_string(0, 45,  (uint8_t*)"WiFi     ?", FONT_MED, 1);
	ssd1306_display_string(80, 0,  (uint8_t*)"CO    ?", FONT_MED, 1);
	ssd1306_display_string(80, 15, (uint8_t*)"CO    ?", FONT_MED, 1);
	ssd1306_display_string(80, 30, (uint8_t*)"PM    ?", FONT_MED, 1);
```

```
	ssd1306_display_string(80, 45, (uint8_t*)"Ext   ?", FONT_MED, 1);
	ssd1306_update();

	//--------------------------------------------------
	//Checking for modules
	// SD card
	if (sd.init())
	{
		if (sd.check_sd_formatted(&cDate) == 0)
		{
			ssd1306_display_string(0, 0, (uint8_t*)"SD card  OK", FONT_MED, 1);
			sd.load_config_file(&cfg);
		}
		else			//SD not formatted
		{
			ssd1306_clear_screen(0);
			ssd1306_display_string_up(0, 0, (uint8_t*)"SD card not formatted",
FONT_MED, 1);
			//ssd1306_display_string(0, 0, (uint8_t*)"Press OK to format, down to skip",
FONT_MED, 1);

			wait_for_keypress();
			if (key_status == Key_OK)
				//sd.format();
		}
	}
	else
	{
		ssd1306_display_string_up(0, 0, (uint8_t*)"SD card   X", FONT_MED, 1);
	}

	//Initialize BMP085 pressure/temperature sensor
	if (bmp.begin())
	{
		ambient_temp = bmp.readTemperature();
		pressure = bmp.readPressure();
		ssd1306_display_string_up(0, 15, (uint8_t*)"Pressure OK", FONT_MED, 1);
	}
	else
		ssd1306_display_string_up(0, 15, (uint8_t*)"Pressure  X", FONT_MED, 1);

	//Initialize humidity sensor
	if (humid.init() == 0)
	{
		humid.getHumidity(&ambient_temp);
		humid.getTemperature(&ambient_temp);
		ssd1306_display_string_up(0, 30, (uint8_t*)"Humidity OK", FONT_MED, 1);
	}
	else
		ssd1306_display_string_up(0, 30, (uint8_t*)"Humidity  X", FONT_MED, 1);

	//Initialize ESP8266
	if (wifi.init())
	{
		wifi.get_mac();
```

```
		ssd1306_display_string_up(0, 45, (uint8_t*)"WiFi     OK", FONT_MED, 1);
	}
	else
		ssd1306_display_string_up(0, 45, (uint8_t*)"WiFi      X", FONT_MED, 1);

	//Initialize CO sensor
	if (co.init() == 0)
	{
		co_level = co.read_blocking(ambient_temp);
		ssd1306_display_string_up(80, 0, (uint8_t*)"CO   OK", FONT_MED, 1);
	}
	else
		ssd1306_display_string_up(80, 0, (uint8_t*)"CO    X", FONT_MED, 1);

	//Initialize CO2 sensor
	if (co2.init())
	{
		co2.request();
		ssd1306_display_string_up(80, 15, (uint8_t*)"CO2  OK", FONT_MED, 1);
	}
	else
		ssd1306_display_string_up(80, 15, (uint8_t*)"CO2   X", FONT_MED, 1);

	//Initialize particulate matter sensor
	if (pm.init())
	{
		pm.request();
		ssd1306_display_string_up(80, 30, (uint8_t*)"PM   OK", FONT_MED, 1);
	}
	else
		ssd1306_display_string_up(80, 30, (uint8_t*)"PM    X", FONT_MED, 1);

	//If no 5V sensors are present, power down 5V output
	if (!pm.is_present() & !co2.present)
		pm.power(false);

	HAL_Delay(500);

	ssd1306_display_string_up(80, 45, (uint8_t*)"Ext   X", FONT_MED, 1);

	read_timer(true);					//Start the 1s read timer interrupt
	HAL_Delay(500);

	//--------------------------------------------------------------------------------
	// Main loop
	while (1)
	{
		//User interface
		ssd1306_clear_screen(0);		//clear screen buffer

		if (key_status)			//If key pressed
		{
			short_beep(true, 10, 0);

			if (key_status == Key_Up)
```

```
		{
			menu_scroll(-1);
			entering_settings = 0;
		}
		else if (key_status == Key_Down)
		{
			menu_scroll(1);
			entering_settings = 0;
		}
		else if (key_status == Key_OK)
		{
			key_ok_pressed = true;
			//alarm_on = false; will just keep enabling
		}

		key_status = Key_None;
	}

	//Display a menu screen
	switch (menu)
	{
	case mnuMain:
		uint8_t buff[50];
		//Temperature
		sprintf((char *)buff, "%0.1f C", log.temperature);
		ssd1306_display_string(25, 0, buff, FONT_LARGE, 1);

		//Humidity
		sprintf((char*)buff, "%02d%%", log.humidity);
		ssd1306_display_string(85, 0, buff, FONT_LARGE, 1);

		//Pressure
		//sprintf((char*)buff, "P %3dkPa", log.pressure/1000);
		//ssd1306_display_string(0, 15, buff, FONT_MED, 1);

		//CO
		ssd1306_display_string(0, 20, (uint8_t*)"CO:", FONT_MED, 1);
		if(!co.present)
			sprintf((char*)buff, " - ppm");
		else if (log.co > (100 * 1000))
			sprintf((char*)buff, "%0.0f ppm", log.co / 1000.0);
		else
			sprintf((char*)buff, "%0.1f ppm", log.co / 1000.0);
		ssd1306_display_string(46, 20, buff, FONT_MED, 1);

		//CO2
		ssd1306_display_string(0, 20+15, (uint8_t*)"CO2:", FONT_MED, 1);
		if (!co2.present)
			sprintf((char*)buff, "- ppm");
		else
			sprintf((char*)buff, "%4d ppm", log.co2);
		ssd1306_display_string(40, 20+15, buff, FONT_MED, 1);

		//PM 2.5/10
		if (!pm.is_present())
```

```
					ssd1306_display_string(0, 20 + 30, (uint8_t*)"PM: -", FONT_MED,
1);
				else
				{
					ssd1306_display_string(0, 20 + 30, (uint8_t*)"PM:", FONT_MED, 1);
					if (log.pm2 > 1000)
						sprintf((char*)buff, "%0.0f,", log.pm2);
					else
						sprintf((char*)buff, "%0.1f,", log.pm2);
					ssd1306_display_string(35, 20 + 30, buff, FONT_MED, 1);

					if (log.pm10 > 1000)
						sprintf((char*)buff, "%0.0f", log.pm10);
					else
						sprintf((char*)buff, "%0.1f", log.pm10);
					ssd1306_display_string(70, 20 + 30, buff, FONT_MED, 1);
				}
				ssd1306_draw_bitmap(100, 64-12, &icon_ugm3_small[0], 8, 12); //units
				break;

			case mnuClock:
				display_time();
				break;

			case mnuGraph:
				//iterate through the graph types
				if (key_ok_pressed)
				{
					if (graph_num == Graph::GRAPH_Last)
						graph_num = Graph::GRAPH_First;
					else
						graph_num =
static_cast<Graph::Graph_type>(static_cast<int>(graph_num) + 1);
				}

				grph.draw_graph(graph_num);

			case mnuSettings:
				//Show settings message, then after timeout show list of settings
				if (entering_settings < 10)
				{
				ssd1306_display_string(25, 0, (uint8_t*)"Settings", FONT_LARGE, 1);
				ssd1306_update();
				entering_settings++;
				}
				else
					display_settings();
				break;

			case mnuAbout:
				ssd1306_display_string(0, 0, (uint8_t*)"Air quality monitor", FONT_MED, 1);
				ssd1306_display_string(0, 20, (uint8_t*)"Build:", FONT_MED, 1);
				ssd1306_display_string(40, 20, (uint8_t*)build_date, FONT_MED, 1);
				ssd1306_display_string(0, 40, (uint8_t*)"Thomas Price", FONT_MED, 1);
				break;
```

```
default:
		break;
}

//Draw arrows depending on menu screen
if (menu == mnuFirst)
		ssd1306_draw_bitmap(121, 58, &icon_down_arrow[0], 7, 6);
else if (menu == mnuLast)
		ssd1306_draw_bitmap(121, 0, &icon_up_arrow[0], 7, 6);
else
{
		ssd1306_draw_bitmap(121, 0, &icon_up_arrow[0], 7, 6);
		ssd1306_draw_bitmap(121, 58, &icon_down_arrow[0], 7, 6);
}

key_ok_pressed = false;
ssd1306_update();
green_led(!green_led_state());
delay_ms(50);

//-----------------------------------------------------------------------------
//Logging
if (new_sensor_read)
{
		//Get the last readings + update graphs
		rtc_get_time_and_date(&log.time, &log.date);

		log.pm2 = pm.get_pm25_level();
		log.pm10 = pm.get_pm10_level();
		log.co = co_level;
		log.co2 = co2.get_co2_level();
		log.humidity = humidity;
		log.temperature = ambient_temp;
		log.pressure = pressure;

		//check for high levels of pm/co/co2
		if (cfg.audio_alarm)
		{
				if (log.pm2 > cfg.pm2_alarm)
						alarm_on = true;
				else if (log.pm10 > cfg.pm10_alarm)
						alarm_on = true;
				else if (log.co > cfg.co_alarm_ppm * 1000)		//co in PPB
						alarm_on = true;
				else if (log.co2 > cfg.co2_alarm_ppm)
						alarm_on = true;
				else
						alarm_on = false;
		}

		if (sd.present & new_SD_save)
				sd.save_log(&log);

		grph.update(&log);				//Update display graphs with new data
```

```
			//Start new readings
			if (pm.is_present() && new_co2_read)		//do slower PM updates
				pm.request();
			if (humid.present)
			{
				humid.getHumidity(&humidity);
				humid.getTemperature(&ambient_temp);
				ambient_temp -= 3.0;  //Offset due to self heating (power supply)
		}
			if (bmp.present)
				pressure = bmp.readPressure();
			if (co.present)
				co_level = co.read_blocking(ambient_temp);
			if (co2.present && new_co2_read)
				co2.request();

			new_sensor_read = false;
			new_co2_read = false;
			new_SD_save = false;
		}


		//If date = next day, start a new log file
		if (new_day)
		{
			new_day = false;
			//sd.shutdown();
			//sd.check_sd_formatted();
		}
	}
}


//=========================================================
// Once button is pressed, interrupt will come here
void HAL_GPIO_EXTI_Callback(uint16_t GPIO_Pin)
{
	if (GPIO_Pin == Button_left_Pin)
		key_status = Key_Up;
	else if (GPIO_Pin == Button_right_Pin)
		key_status = Key_Down;
	else if (GPIO_Pin == Button_OK_Pin)
		key_status = Key_OK;
	else
		Error_Handler();
}

/** System Clock Configuration */
{removed}

/**
* @brief  Display settings menu screen
* @param  None
* @retval None
```

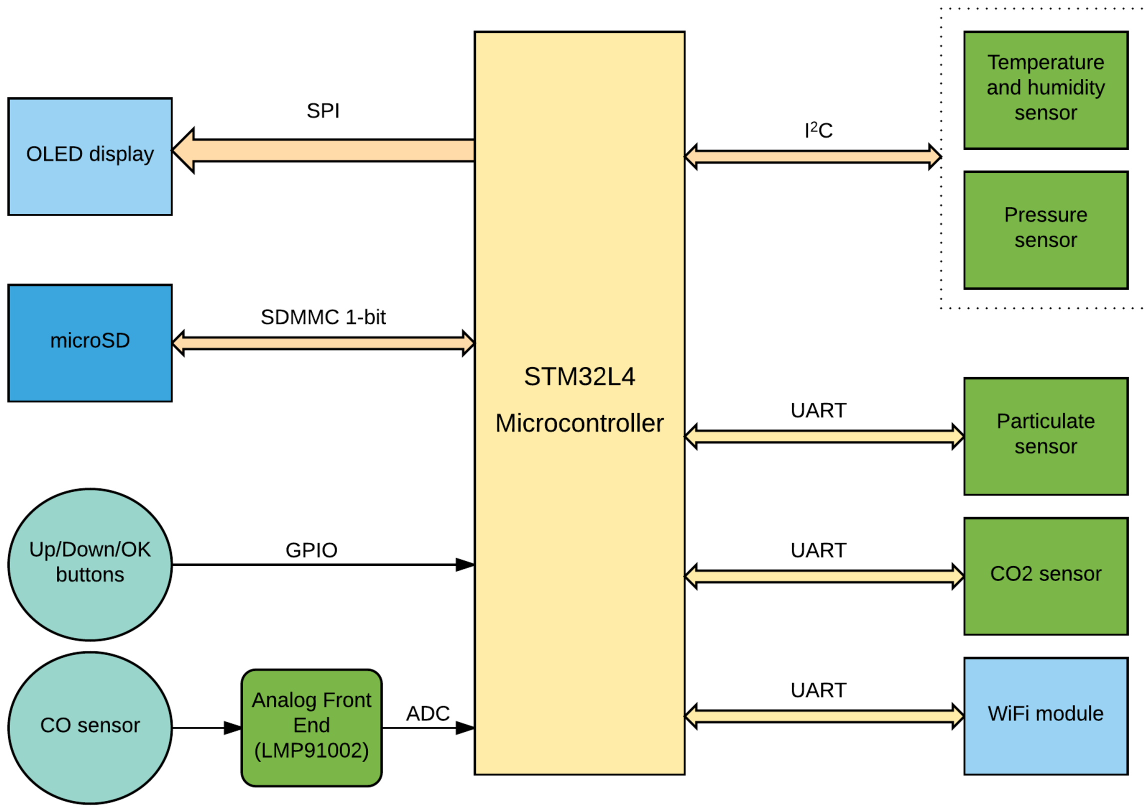
```
*/
void display_settings(void)
{
	if (cfg.button_beep)
		ssd1306_display_string(0, 0, (uint8_t*)"Key beep: ON", FONT_MED, 1);
	else
		ssd1306_display_string(0, 0, (uint8_t*)"Key beep: OFF", FONT_MED, 1);

	if (cfg.audio_alarm)
		ssd1306_display_string(0, 15, (uint8_t*)"Audio alarm: ON", FONT_MED, 1);
	else
		ssd1306_display_string(0, 15, (uint8_t*)"Audio alarm: OFF", FONT_MED, 1);

	ssd1306_display_string(0, 30, (uint8_t*)"Serv: ", FONT_MED, 1);
	ssd1306_display_string(30, 30, (uint8_t*)cfg.server, FONT_MED, 1);

	ssd1306_display_string(0, 45, (uint8_t*)"SSID: ", FONT_MED, 1);
	ssd1306_display_string(30, 45, (uint8_t*)cfg.wifi_ap, FONT_MED, 1);
}


/**
  * @brief  Display time and date on the LCD
  * @param  None
  * @retval None
  */
void display_time(void)
{
	uint8_t buff[50];

	if (sd.present)
		ssd1306_draw_bitmap(0, 0, &icon_download[0], 8, 8); //If SD card present put symbol

	if (cfg.audio_alarm)
		ssd1306_draw_bitmap(12, 0, &c_chAlarm88[0], 8, 8); //If alarm enabled, put symbol

	if(wifi.present)
		ssd1306_draw_bitmap(24, 0, &c_chSingal816[0], 16, 8); //If Wifi connected, put symbol

	HAL_RTC_GetTime(&hrtc, &cTime, RTC_FORMAT_BIN);
	HAL_RTC_GetDate(&hrtc, &cDate, RTC_FORMAT_BIN);


	/* Display time Format : hh:mm:ss */
	sprintf((char *)buff, "%02d:%02d:%02d", cTime.Hours, cTime.Minutes, cTime.Seconds);
	ssd1306_draw_3216str(0, 16, buff);

	/* Display date Format : mm-dd */
	sprintf((char*)buff, "20%02d-%02d-%02d", cDate.Year, cDate.Month, cDate.Date);
	ssd1306_display_string(30, 50, buff, FONT_MED, 1);
}

/**
  * @brief  Output of green LED next to processor
  * @param  On or Off state of LED
```

```
  * @retval None
  */

void green_led(bool state)
{
	if (state)
		HAL_GPIO_WritePin(Green_LED_GPIO_Port, Green_LED_Pin, GPIO_PIN_SET);
	else
		HAL_GPIO_WritePin(Green_LED_GPIO_Port, Green_LED_Pin, GPIO_PIN_RESET);
}

/**
  * @brief			Scroll up or down in the menu
  * @param dir: Direction to scroll the menu (- or +)
  * @retval			None
  */
void menu_scroll(int8_t dir)
{
	int i = (int) menu + dir;

	if (i < 0)					//Bottom of menu
		i = 0;					//i = (int)mnuSettings;

	else if (i > (int)mnuLast) //Top of menu
		i = (int)mnuLast;  //i = (int)mnuMain;

	menu = (menuScreens)i;
}

/**
  * @brief  Activate piezo buzzer for short beep
  * @param  state:
  * @param  time:
  * @param  frequency:
  * @retval None
  */
void short_beep(bool state, uint32_t time, uint32_t frequency)
{
#if	BEEP_ON
	HAL_TIM_Base_Start_IT(&htim2);				//start timeout timer
	HAL_TIM_OC_Start(&htim16, TIM_CHANNEL_1)		//start piezo buzzer
#endif
	piezo_on_time = time;
}
```

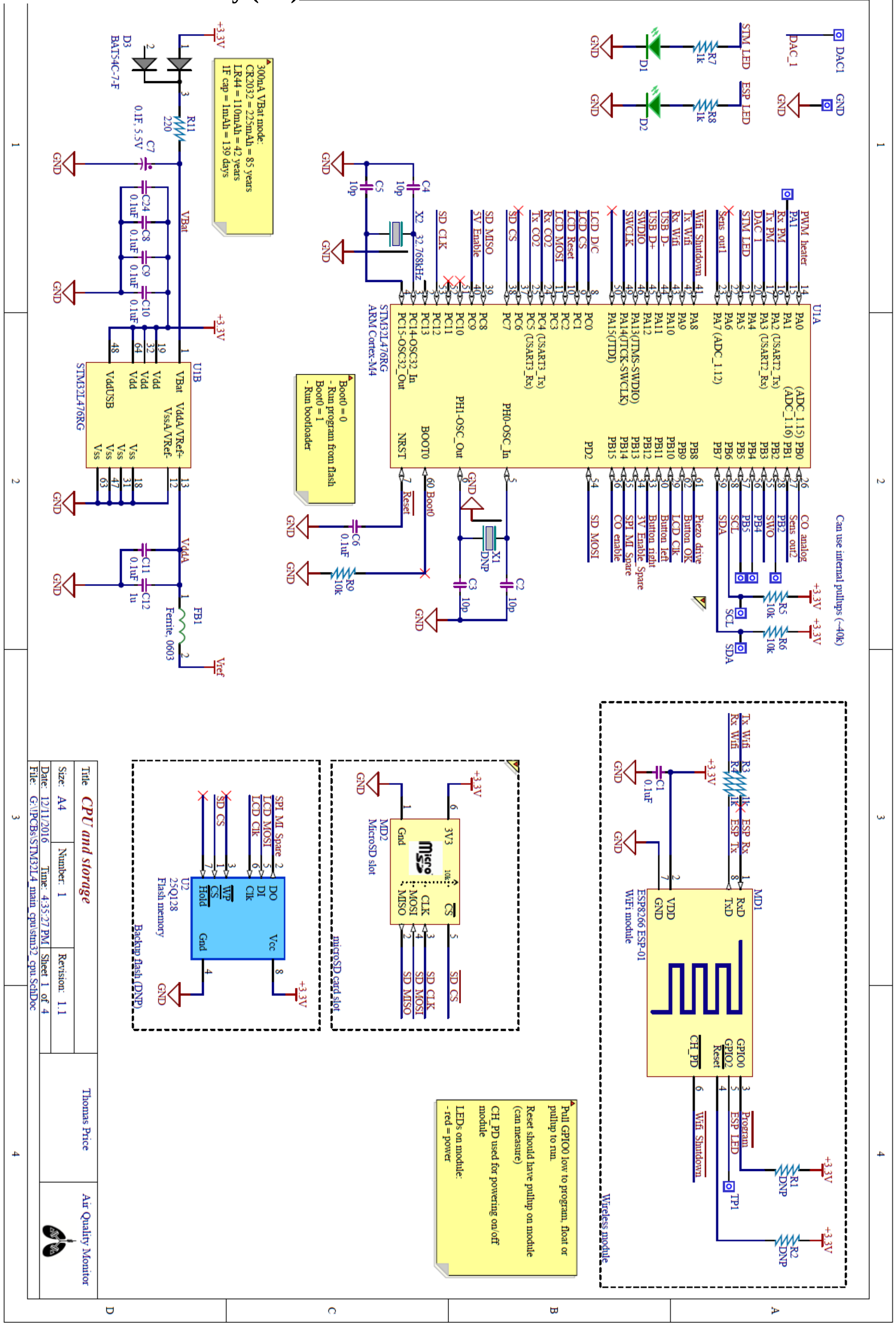
11 APPENDIX B: SCHEMATICS AND DRAWINGS

11.1 Electrical Drawings – Schematic

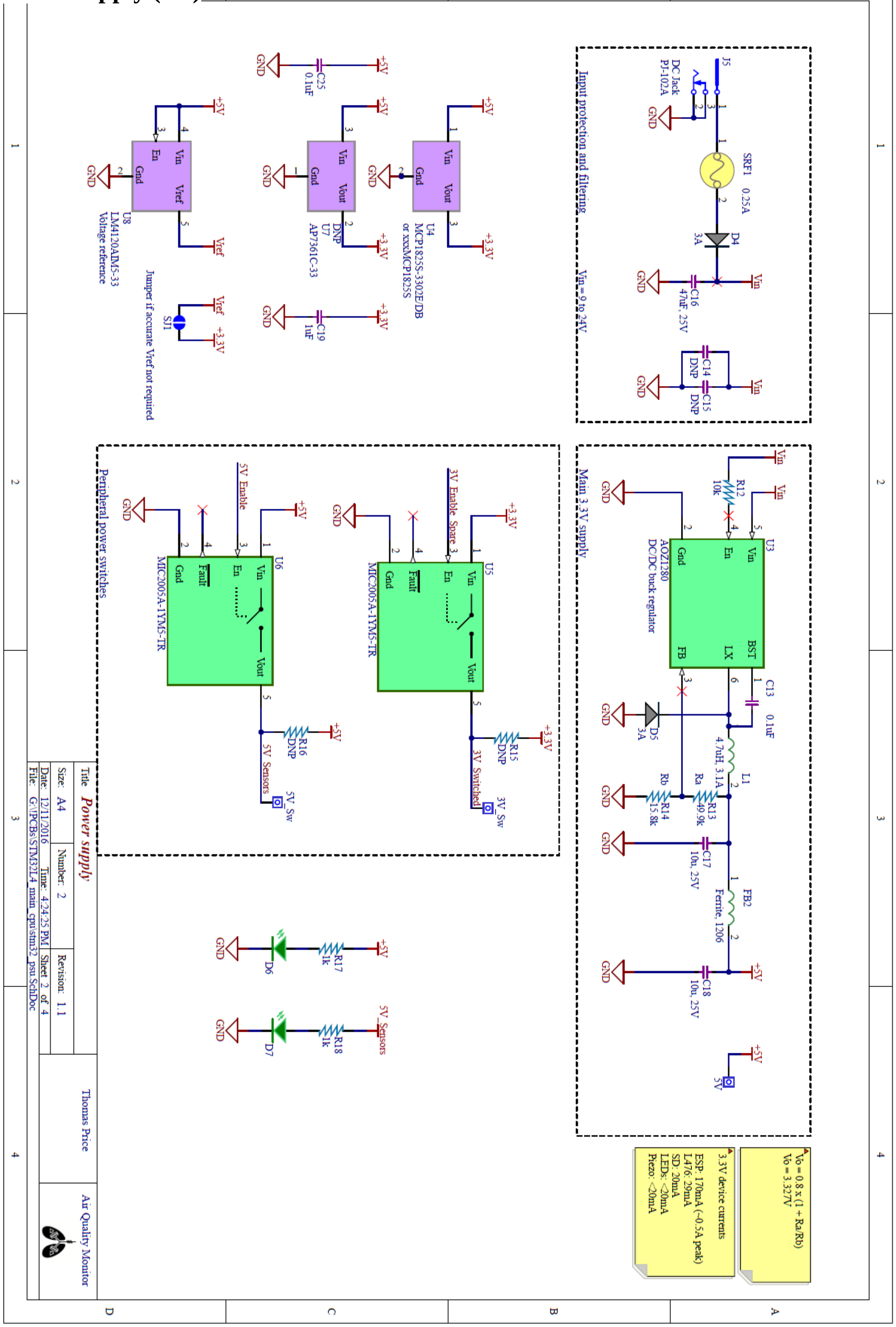
System level diagram



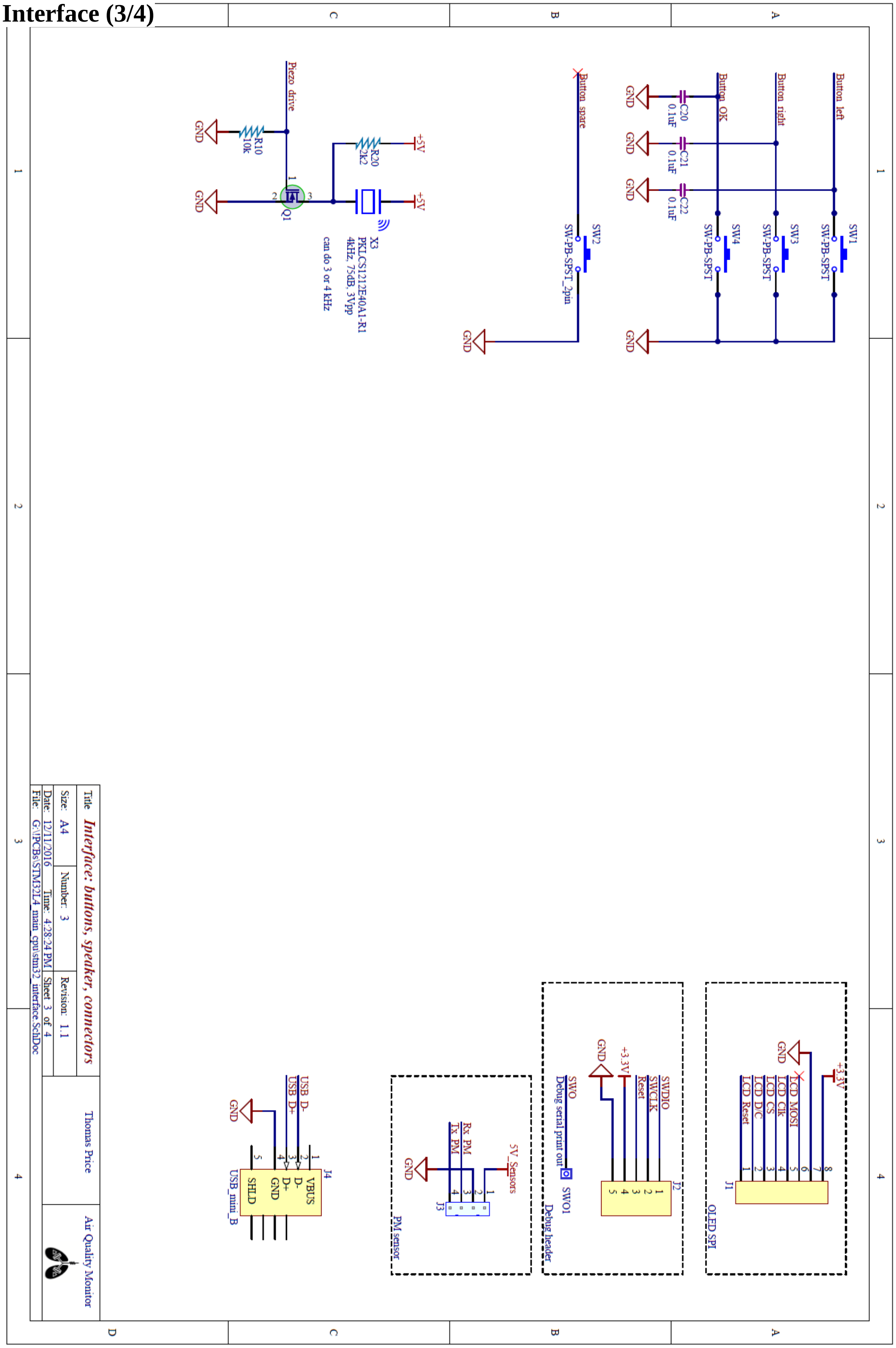
Processor and memory (1/4)



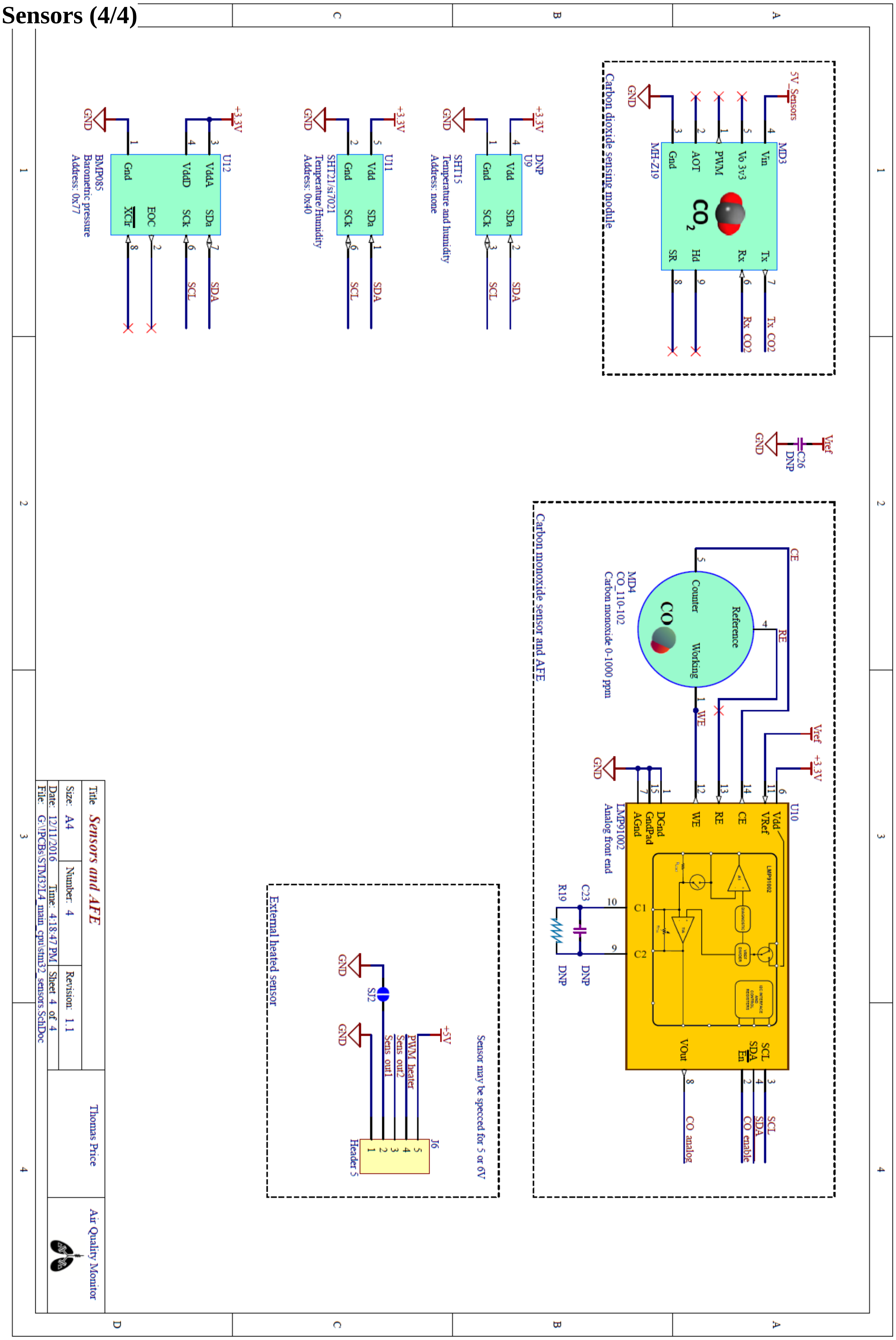
Power supply (2/4)



Interface (3/4)



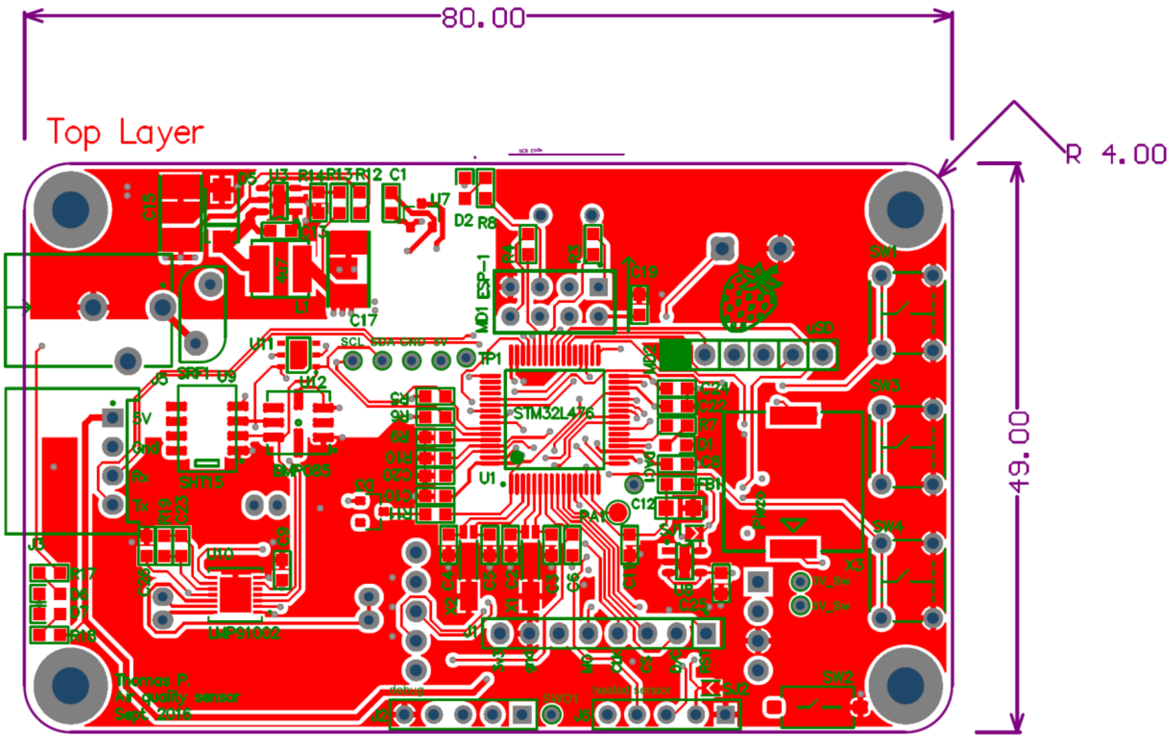
Sensors (4/4)



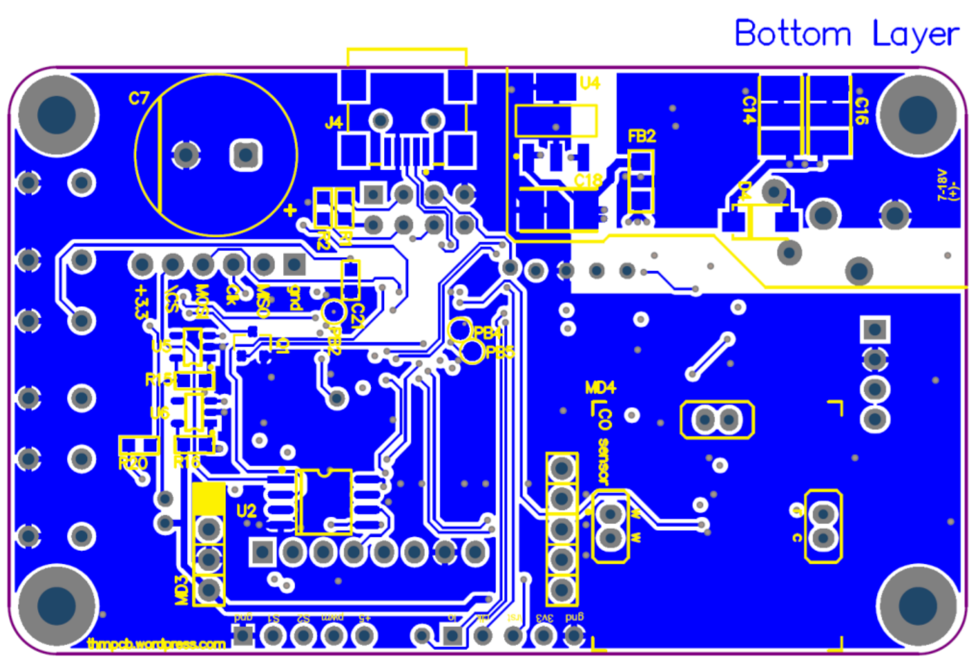
Carbon dioxide sensing module
5V_Sensors
MD3
MH-Z19
Vin
Vo 3v3
PWM
AOT
Gnd
Tx
Rx
Hd
SR
Tx CO2
Rx CO2
GND
Vref
C26
DNP
Carbon monoxide sensor and AFE
CE
RE
WE
MD4
CO_110-102
Carbon monoxide 0-1000 ppm
Reference
Counter
Working
U10
LMP91002
Analog front end
Vdd
VRef
CE
RE
WE
DGnd
GndPad
AGnd
C1
C2
SCL
SDA
En
VOut
C23
DNP
R19
DNP
CO analog
CO enable
+3.3V
DNP
U9
SHT15
Temperature and humidity
Address: none
U11
SHT21/si7021
Temperature/Humidity
Address: 0x40
U12
BMP085
Barometric pressure
Address: 0x77
Vdd
SDa
SCk
VddA
VddD
EOC
XCLR
SDA
SCL
External heated sensor
Sensor may be specced for 5 or 6V
+5V
PWM_heater
Sens_out2
Sens_out1
J6
Header 5
SJ2
Title Sensors and AFE
Size: A4
Number: 4
Revision: 1.1
Date: 12/11/2016
Time: 4:18:47 PM
Sheet 4 of 4
File: G:\PCBs\STM32L4 main_cpu\stm32_sensors.SchDoc
Thomas Price
Air Quality Monitor

11.2 Electrical Drawings – PCB

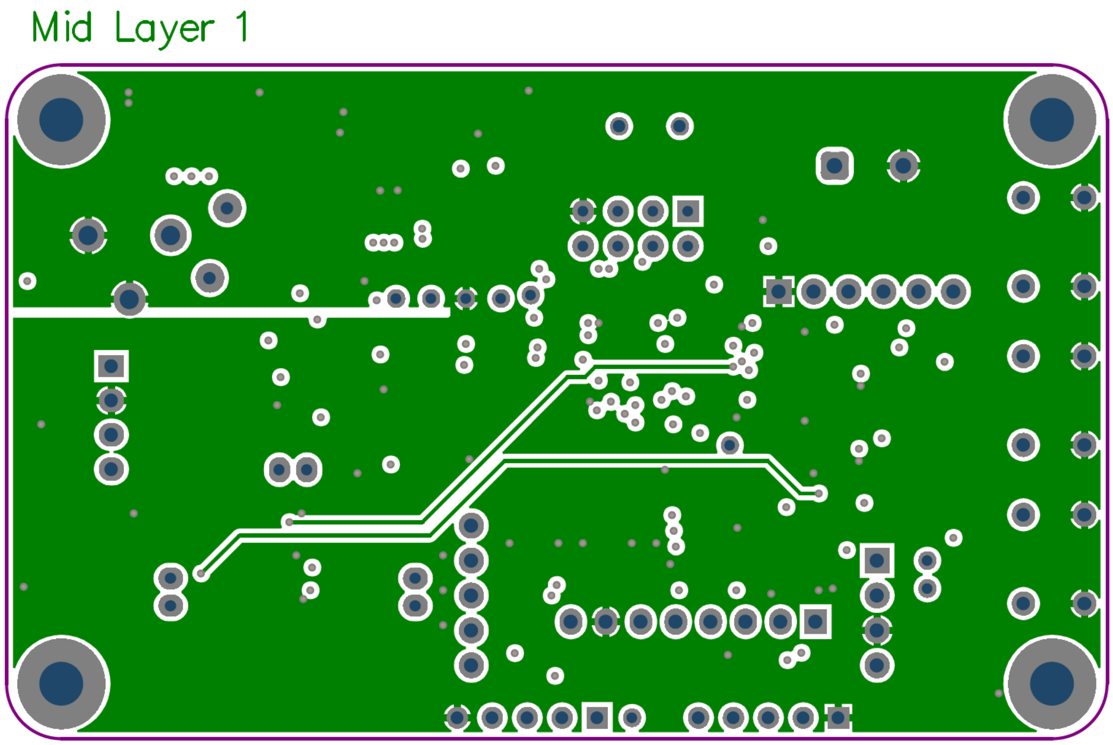
Top copper and silkscreen layer



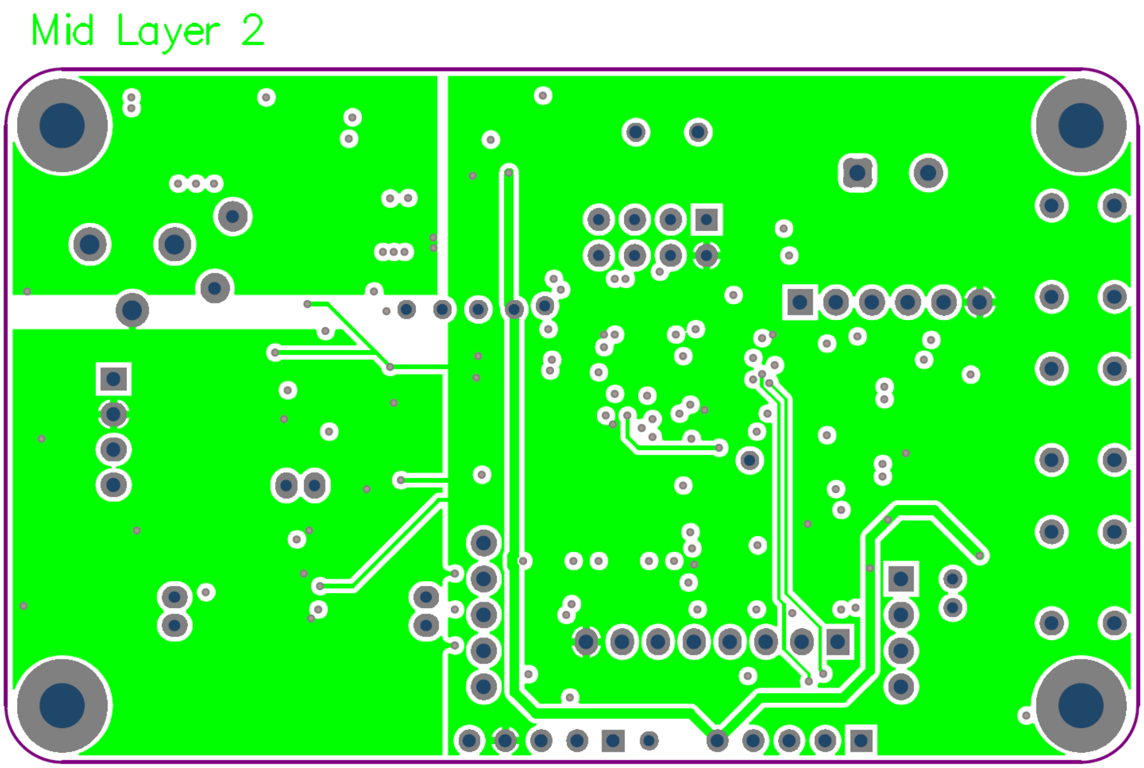
Bottom copper and silkscreen



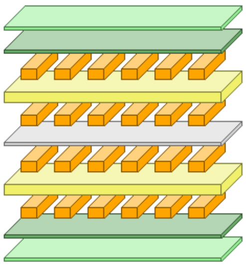
Mid layer 1



Mid layer 2



PCB stack-up



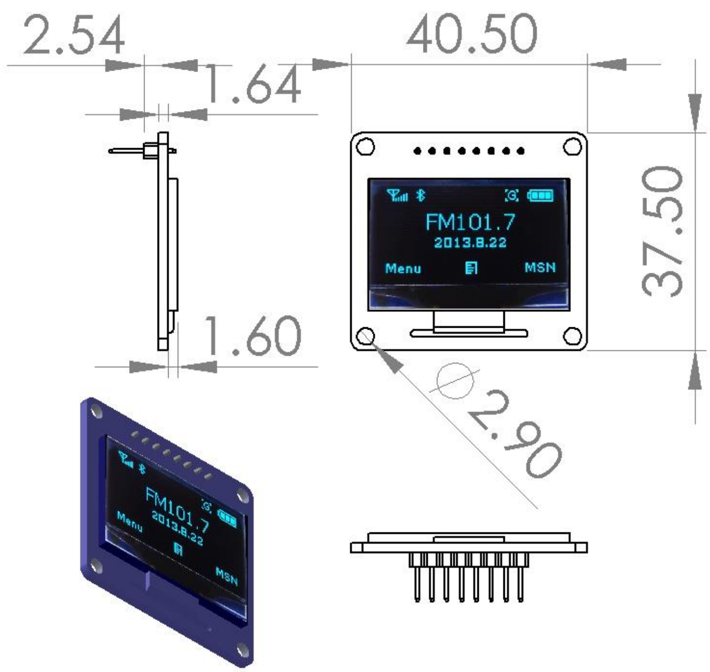
Layer Name	Type	Material	Thickness (mil)	Dielectric Material	Dielectric Constant	Pullback (mil)	Orientation
Top Overlay	Overlay						
Top Solder	Solder Mask/Co...	Surface Material	0.4	Solder Resist	3.5		
Top Layer	Signal	Copper	1.4				Top
Dielectric1	Dielectric	Core	10	FR-4	4.8		
Mid Layer 1	Signal	Copper	1.4				Not Allowed
Dielectric 3	Dielectric	Prepreg	37	FR-4	4.2		
Mid Layer 2	Signal	Copper	1.4				Not Allowed
Dielectric 2	Dielectric	Core	10	FR-4	4.2		
Bottom Layer	Signal	Copper	1.4				Bottom
Bottom Solder	Solder Mask/Co...	Surface Material	0.4	Solder Resist	3.5		
Bottom Overlay	Overlay						

Total PCB thickness = 1.6mm

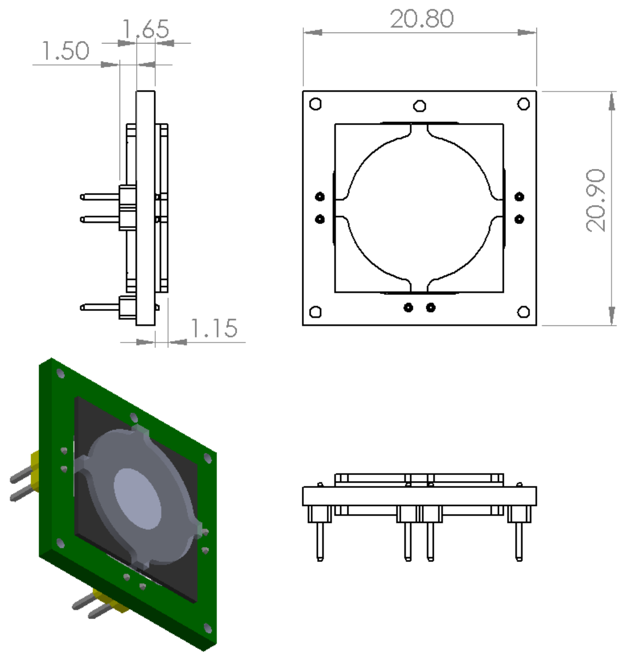
11.3 Mechanical Drawings

Models used in the project are available online: grabcad.com/thmjpr/projects

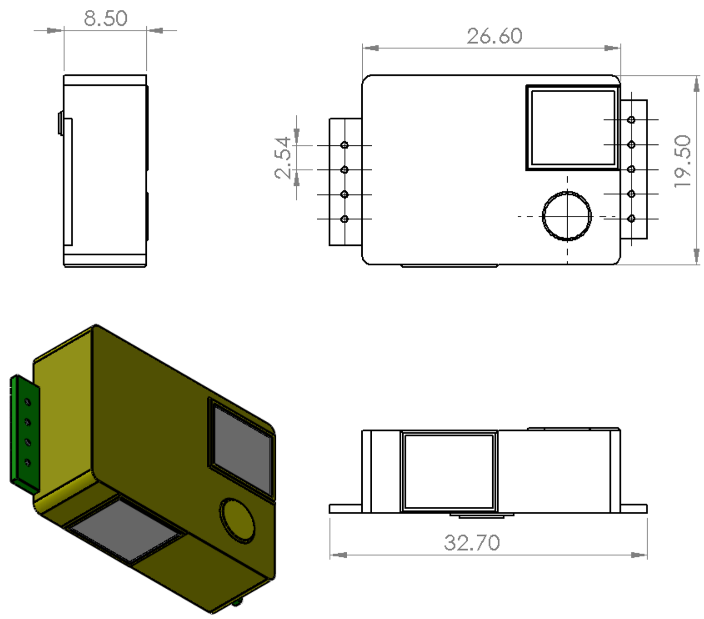
1.3” OLED display



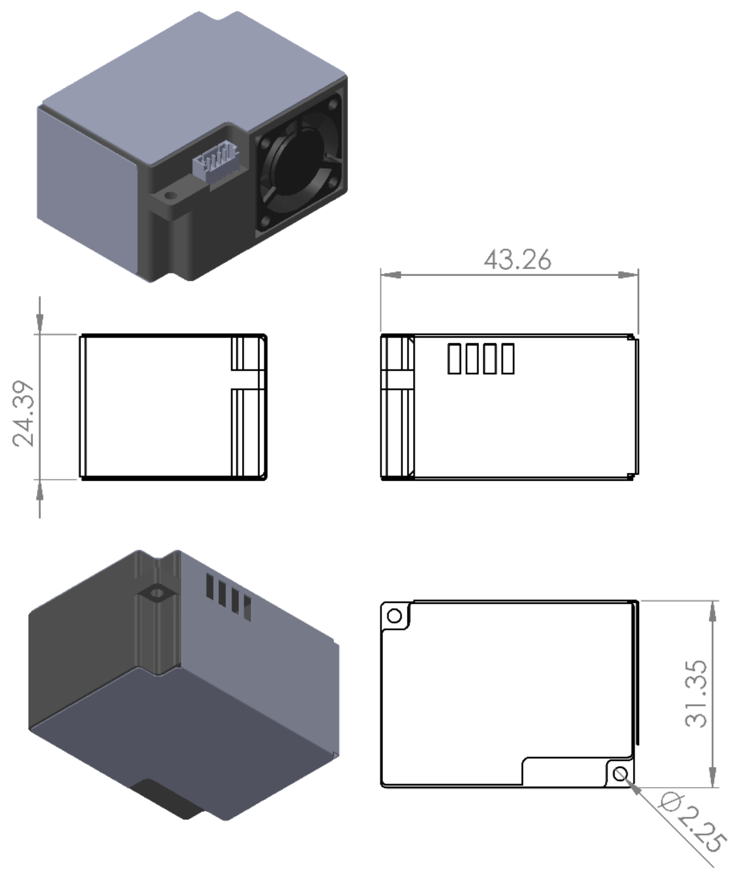
Spec Carbon Monoxide sensor (CO 110-102)



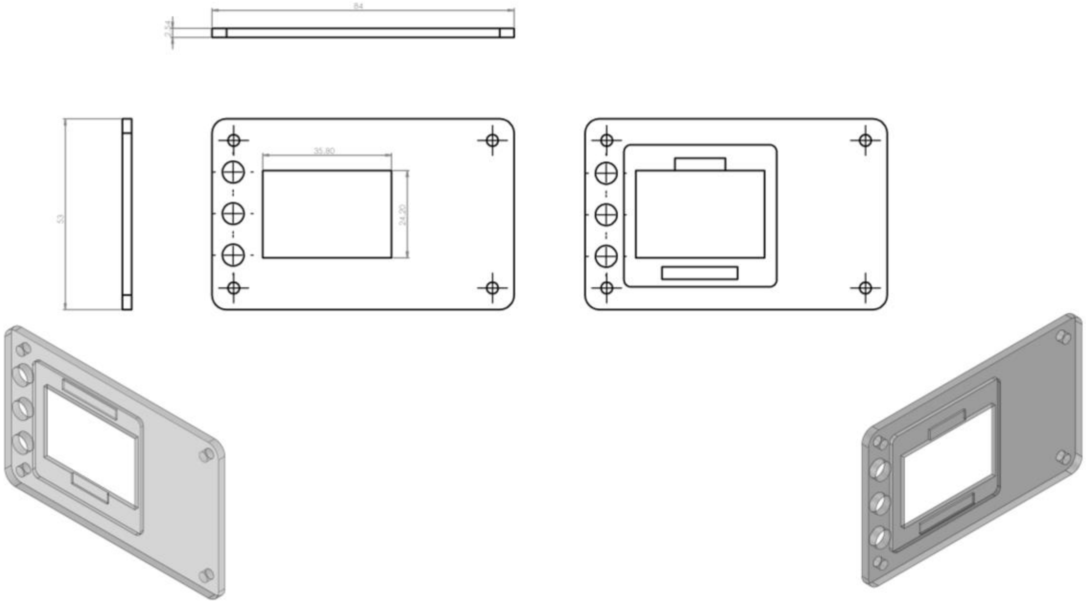
MH-Z19 CO2 sensor



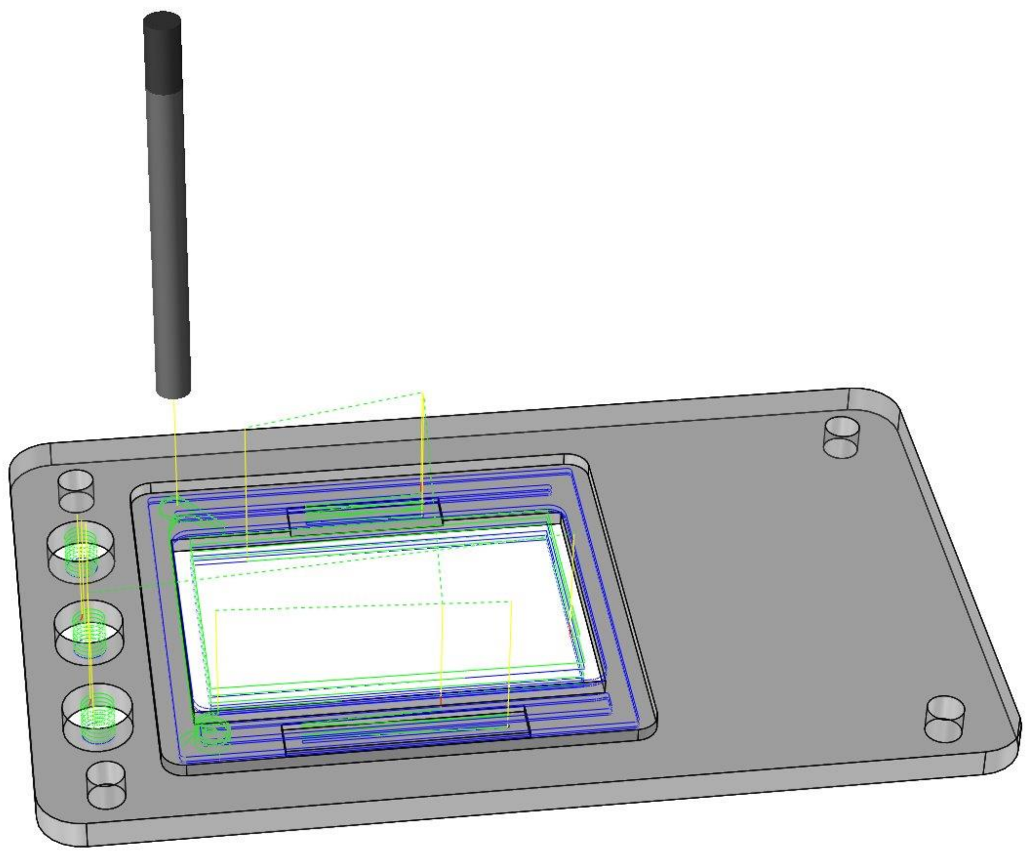
SDS021 particulate matter sensor



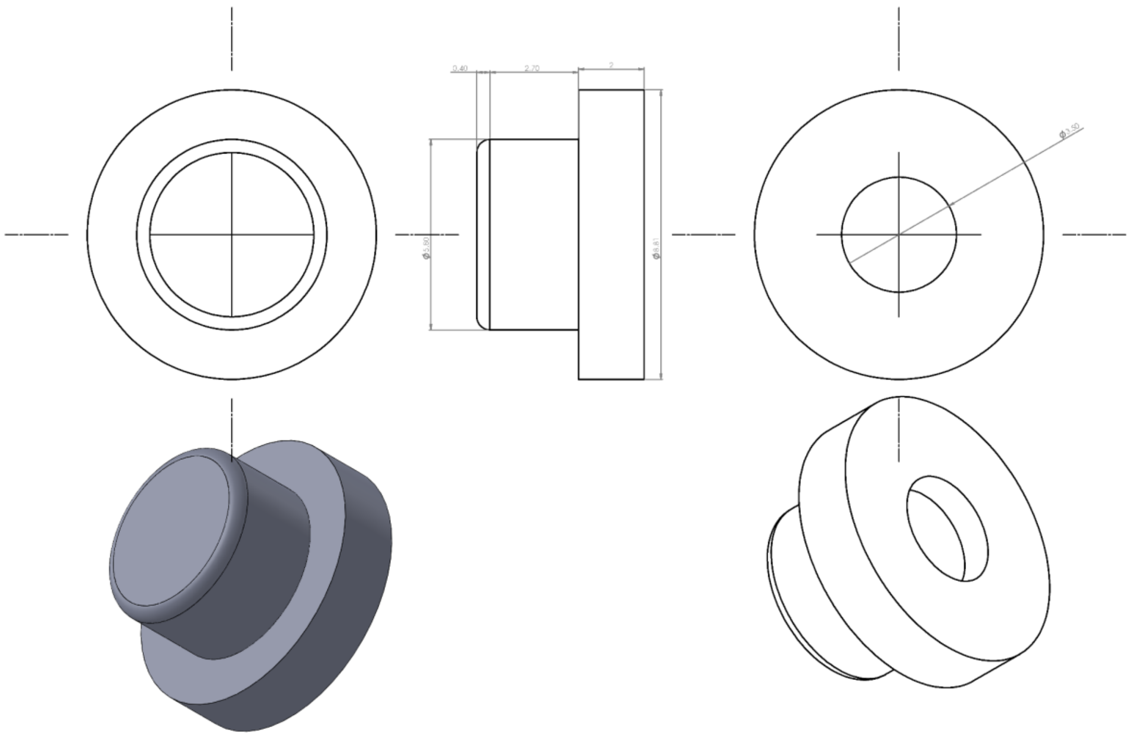
Top machined acrylic plate



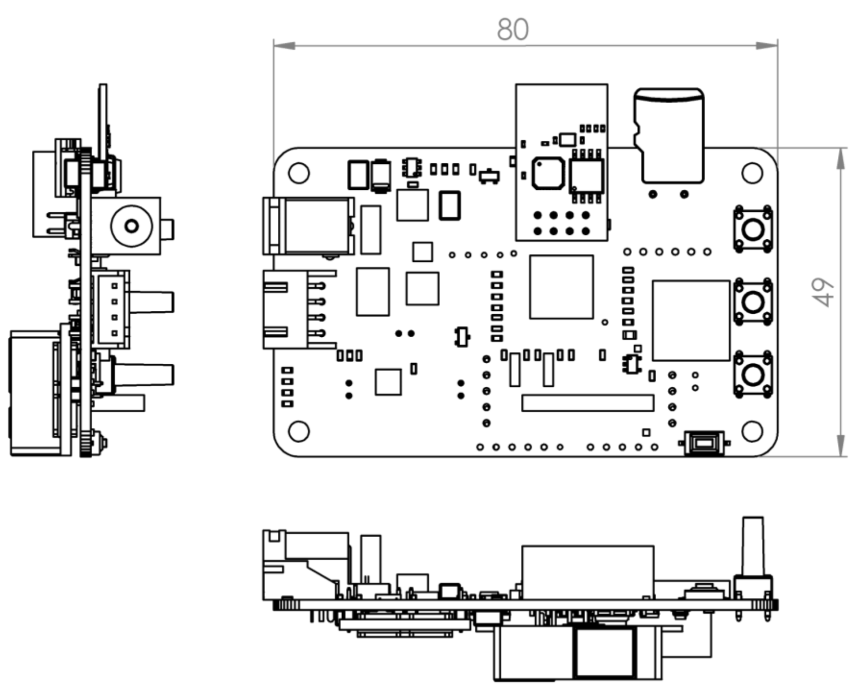
Top plate toolpath

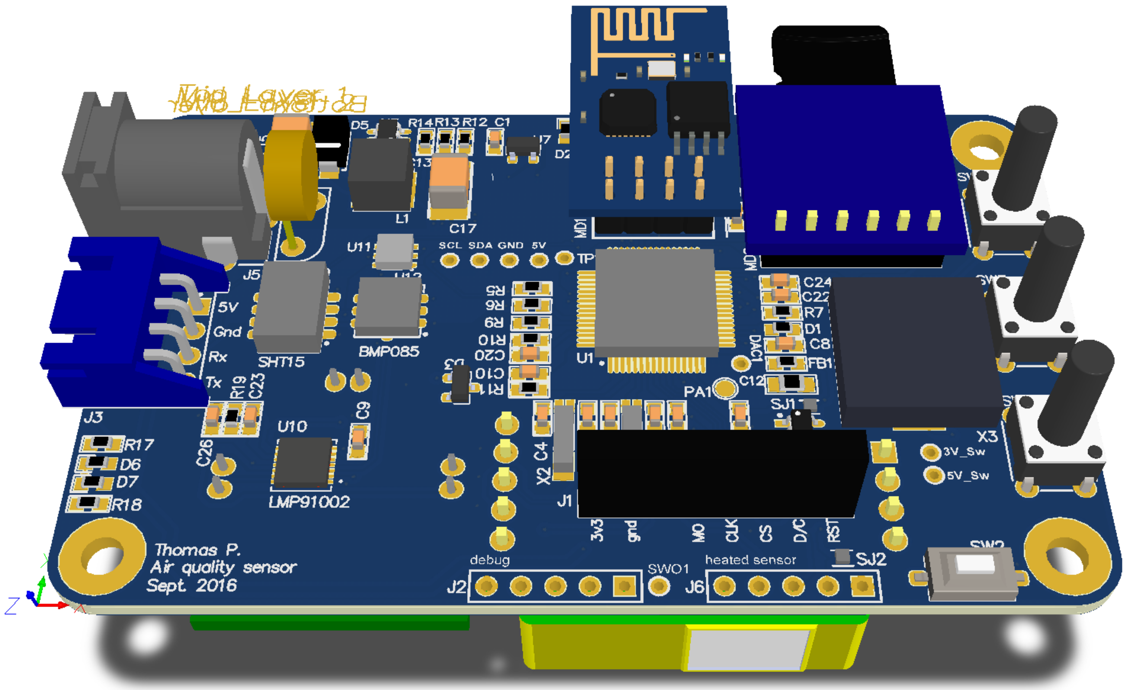


Aluminum button



PCB assembly




Thomas P.
Air quality sensor
Sept. 2016
SHT15
BMP085
LMP91002
5V
Gnd
Rx
Tx
debug
heated sensor
SWO1
3V_Sw
5V_Sw
SCL
SDA
GND
5V
3v3
gnd
MO
CLK
CS
D/C
RST

12 APPENDIX C: BILL OF MATERIALS

Circuit board assembly Bill of Materials

Designator	Manufacturer	Manufacturer Part Number	Description	Footprint	Quantity	Price (ea)	Price
C1, C6, C8, C9, C10, C11, C13, C20, C21, C22, C24, C25	Generic	10%, 50V, X5R	Ceramic, 0.1uF	0603	12	$0.02	$0.24
C2, C3, C4, C5	Generic	5%, 100V, NP0	Ceramic, 10pF	0603	4	$0.02	$0.08
C7	Kamcap	SE-5R5-D104VY	Supercap, 0.1F, 5.5V	EECF5R5U104	1	$1.05	$1.05
C12	Generic	10%, 25V, X5R	Ceramic, 1uF	0805	1	$0.02	$0.02
C14	Generic	10%, 25V, X5R	Ceramic	1812	DNP	-	-
C15	Generic		Ceramic	1812	DNP	-	-
C16, C17, C18	Generic	10%, 25V, X5R	Ceramic, 10uF	1812	3	$0.10	$0.30
C19	Generic	10%, 25V, X5R	Ceramic, 1uF	0603	1	$0.02	$0.02
C23, C26	Generic		Ceramic	0603	DNP	-	-
D1, D2, D6	Generic	Green LED	LED, Green, 6.9mcd, 20mA	0603	3	$0.05	$0.15
D3	Diodes Inc	BAT54C-7-F	Diode, 200mA, 30V, Schottky Common Cathode	SOT-23	1	$0.05	$0.05
D4, D5	Fairchild Semi	SSA36	Diode, 3A, 60V, Rectifier SMA	SMA	2	$0.20	$0.40
D7	Generic	Yellow LED	LED, Yellow, 6.9mcd, 20mA	0603	1	$0.05	$0.05
FB1	Laird	MI0603J601R-10	Ferrite bead 600 ohm, 1A	0603	1	$0.05	$0.05
FB2	Laird	MI1206L501R-10	Ferrite bead 500 ohm, 2A	1206	1	$0.05	$0.05
J2			Header, 5-Pin	HDR1X5	DNP	-	-
J3	JST	S4B-XH-A(LF)(SN)	CON, Pol-Lock Male, 4, Tin, 2.5mm	JST_S4B_XH_A	1	$0.15	$0.15
J4	Hirose	UX60-MB-5ST	USB 2.0, Right Angle, SMT, A Type, Receptacle	USB mini SMD	1	$0.72	$0.72
J5	CUI Inc	PJ-102A	CON, 2.1mmx5.5mm,	PJ102A	1	$0.49	$0.49
J6			Header, 5-Pin	HDR1X5	DNP	-	-
L1	Taiyo Yuden	NR5040T4R7N	Inductor, 4.7uH, 3.1A, 38mOhm, 30%	NR5040	1	$0.21	$0.21
MD1	AI Thinker	ESP-01	ESP8266 ESP-01	ESP8266 ESP-01	1	$2.20	$2.20
MD2	Generic	MicroSD	MicroSD module, 3.3V, SPI/1-bit	Micro_SD	1	$1.00	$1.00
MD3	Winsen Sensor	MH-Z19	Module, Sensor, co2	MH-Z19	1	$29.00	$29.00

Designator	Manufacturer	Manufacturer Part Number	Description	Footprint	Quantity	Price (ea)	Price
MD4	Spec sensor	110-102	Module, Sensor, carbon monoxide, 0-1000ppm	CO_110-102	1	$30.00	$30.00
Q1	Micro Commercial	SI2302-TP	Trans, N-channel, 20V, 3A	SOT-23	1	$0.22	$0.22
R1, R2, R15, R16, R19	Generic	1%, 1/10W	Resistor, 10k, 1/10W, 1%, Thick Film	0603	DNP	-	-
R3, R4, R7, R8, R17, R18	Generic	1%, 1/10W	Resistor, 1k, 1/10W, 1%, Thick Film	0603	6	$0.02	$0.12
R5, R6, R9, R10, R12	Generic	1%, 1/10W	Resistor, 10k, 1/10W, 1%, Thick Film	0603	5	$0.02	$0.10
R11	Generic	1%, 1/10W	Resistor, 220R, 1/10W, 1%, Thick Film	0603	1	$0.02	$0.02
R13	Generic	1%, 1/10W	Resistor, 49.9k, 1/10W, 1%, Thick Film	0603	1	$0.02	$0.02
R14	Generic	1%, 1/10W	Resistor, 15.8k, 1/10W, 1%, Thick Film	0603	1	$0.02	$0.02
SRF1	Littelfuse Inc	RXEF025-2	Fuse, SRF, 0.25A, 72VDC	RUEF110	1	$0.24	$0.24
SW1, SW3, SW4	TE Connectivity	2-1825910-7	Switch, PB, SPST-NO	SW-PB-4pin-long	3	$0.08	$0.24
SW2			Switch, PB, SPST-NO	SW-PB-SMD-2_3x6	DNP	-	-
U1	STMicroelectronics	STM32L476RGT6	ARM Cortex-M4 32-bit MCU	LQFP64_N	1	$7.77	$7.77
U2	Winbond	W25Q128FVSG	IC, Flash memory, SPI, 128M, 3.3V	SOICN8_5.3mm	DNP	-	-
U3	Alpha and Omega	AOZ1280CI	IC, Buck regulator, 3-26V, 1.2A, 1.5MHz	SOT23-6L	1	$0.36	$0.36
U4	Microchip	MCP1825S-3302E/DB	IC, Reg LDO, 500mA, 3.3V	SOT-223	1	$0.50	$0.50
U5, U6	Micrel	MIC2005A-1YM5	IC, Switch, high-side, 2.5-5.5V, 0.5A	SOT23-5	2	$0.30	$0.60
U7	Diodes Inc	AP7361C-33	IC, Reg LDO, 250mA, 3.3V	SOT-23	DNP	-	-
U8	TI	LM4120AIM5-33	IC, voltage reference, 3.3V, 0.2%	SOT23-5	1	$1.88	$1.88
U9	Sensirion	SHT15	IC, Sensor, temperature, humidity	LCCS-8N	DNP	-	-
U10	TI	LMP91002SD/NOPB	IC, AFE gas sensor, 2.7-3.6V	WSON-14	1	$2.93	$2.93
U11	Sensirion	SI7021-A20-GM	IC, Sensor, temperature, humidity	sht21	1	$3.93	$3.93
U12	Bosch	BMP085	IC, Sensor, pressure	LCC8_5x5	1	$2.90	$2.90

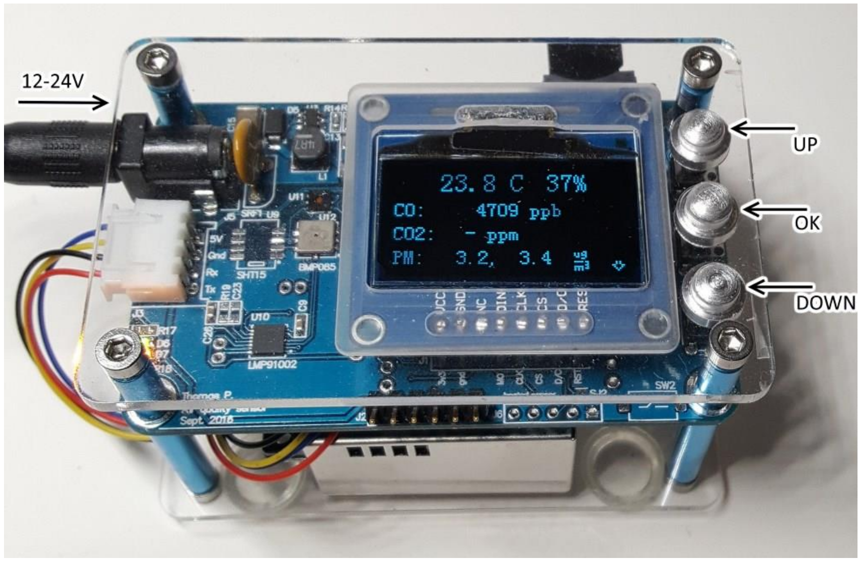
Designator	Manufacturer	Manufacturer Part Number	Description	Footprint	Quantity	Price (ea)	Price
X1	Abracon		OSC, XTAL	AB26TRQ	DNP	-	-
X2	Abracon	AB26TRQ-32.768KHZ-T	OSC, XTAL, 32.768kHz	AB26TRQ	1	$0.31	$0.31
X3	Murata	PKLCS1212E40A1-R1	Buzzer, SMT, 4kHz, 75dB	PKLCS1212E40	1	$1.51	$1.51

Total **$89.90**

Additional Bill of Materials

Manufacturer	Manufacturer Part Number	Description	Quantity	Price (ea)	Price
JST	XHP-5	Mating connector	1	$0.10	$0.10
Inova Fitness	SDS021	Laser particulate matter sensor (PM2.5, PM10)	1	$38.74	$38.74
Seeed studio	DP8049	Acrylic laser cut sheet	2	$3.00	$6.00
Generic	M3	Aluminum threaded standoff	8	$0.50	$4.00
Generic	M3	Stainless steel cap screw	8	$0.10	$0.80
Elecrow	4-layer PCB	Circuit board, 4 layer, 1oz Cu, 1.6mm, 10cm*5cm	1	$8.54	$8.54
Triad magnetics	WSU120-0700	AC/DC adapter 12Vdc, 8W, 5.5x2.1mm, center positive	1	$10.50	$10.50
Waveshare	1.3inch OLED (B)	OLED display, 128x64, 1.3", SPI or I2C	1	$9.49	$9.49
Total					**$78.17**

13 APPENDIX D: INSTRUCTION MANUAL AND SPECIFICATIONS



Operating procedure:

1. Place AQM on stable surface with 5cm free space in all directions.
2. Install 2GB or larger microSD card into card slot.
3. Plug in 12Vdc adapter into barrel jack.
4. AQM will power up and indicate sensors are present and working.
5. Monitor the screen to observe readings.
6. Press down arrow to change to another screen.

Retrieving logs manually

1. Press **Down** button until Settings screen appears.
2. Press **OK**
3. Select "Remove SD card"
4. Pull microSD card to remove from slot.
5. Place SD card in USB card reader and connect to PC.
6. Retrieve log files from the device, in the format "Log-YY-MM-DD.csv"
7. Run Excel program AirQuality_Log_Plotter.xlsm
8. Select button “Open and Plot CSV Data”.
9. Navigate to location of log file.
10. Open and view results.
11. If Excel not available csv file can be opened in LibreOffice or any other plotting tool and manually plotted.

Data format

- ASCII text, comma separated values, first row of csv is the header naming column contents

Field	Date	Time	Temperature	Humidity
Units	MM-DD-YY	HH-MM-SS	Degrees Celsius	Percent
Units symbol	-	-	°C	%

Field	Pressure	CO	CO2	PM2.5 and PM10
Units	Pascals	Parts per million	Parts per million	Micro gram per meter cubed
Units symbol	Pa	ppm	ppm	$\mu g/m^3$

Technical specifications

Power supply	12-24VDC
Current	0.5A maximum
	60mA typical at 12V (0.8W)
Warm up time	3 minutes
CO	0 – 3,000 ppm
CO2	0 – 2,000 ppm
Temperature	-40 – 125 °C
Humidity	0 – 100%
Pressure	0.3 – 1.1 kPa
Particulate matter (2.5)	0 – 1,000 $\mu g/m^3$
Particulate matter (10)	0 – 1,000 $\mu g/m^3$

14 APPENDIX E: LIST OF ABBREVIATIONS & ACRONYMS

ADC Analog to digital converter

A digital circuit that can use various techniques to convert an analog voltage to a digital output result. Input is a continuous infinitely variable potential over time, output is a discrete step in time and voltage, limited to a number of values.

AQM Air quality monitor

CO Carbon monoxide

CO_2 Carbon dioxide

A clear, odorless, tasteless gas produced by mammals as part of respiration.

ESD Electro-static discharge

FLASH Flash memory, non-volatile storage medium.

I^2C Inter-integrated circuit

Two wire multi-slave serial communications bus, lines are switched with open-drain outputs.

IC Integrated circuit

Semiconductor material (often silicon) on which an electronic circuit has been etched using photolithography process.

LED Light emitting diode

P-N junction semiconductor diode which emits light when specific voltage is reached.

MEMS Microelectromechanical systems

PM2.5 Particulate Matter 2.5 micrometers

	Fine airborne particulate matter with an aerodynamic diameter of less than 2.5 micrometers.
PM10	Particulate Matter 10 micrometers
	Fine airborne particulate matter with an aerodynamic diameter of less than 10 micrometers.
PPM	Parts per million
PPB	Parts per billion
PWM	Pulse width modulation
	Varying the duty cycle (high time vs low time) of a fixed period square wave.
RTC	Real-time clock
	An always running accurate timekeeping method using a low power clock source (such as 32kHz crystal oscillator). Can be a peripheral device or purchased as a standalone IC.
SPI	Serial peripheral interface
SRF	Self-resonant frequency
SRF(2)	Self resetting fuse
	A component composed of positive temperature coefficient material. When too much current is passed, resistance will rise enough to protect the downstream circuit. Once the device cools resistance will drop again, i.e. reset.
UART	Universal asynchronous receiver/transmitter
VOC	Volatile organic compounds

15 APPENDIX F: MEASUREMENT DATA

Measurements were made during design phase and research phase. They may be useful for others attempting to make a similar product.

Board component measurements

- Taken at: 5V supply, 22C ambient, 55% humidity

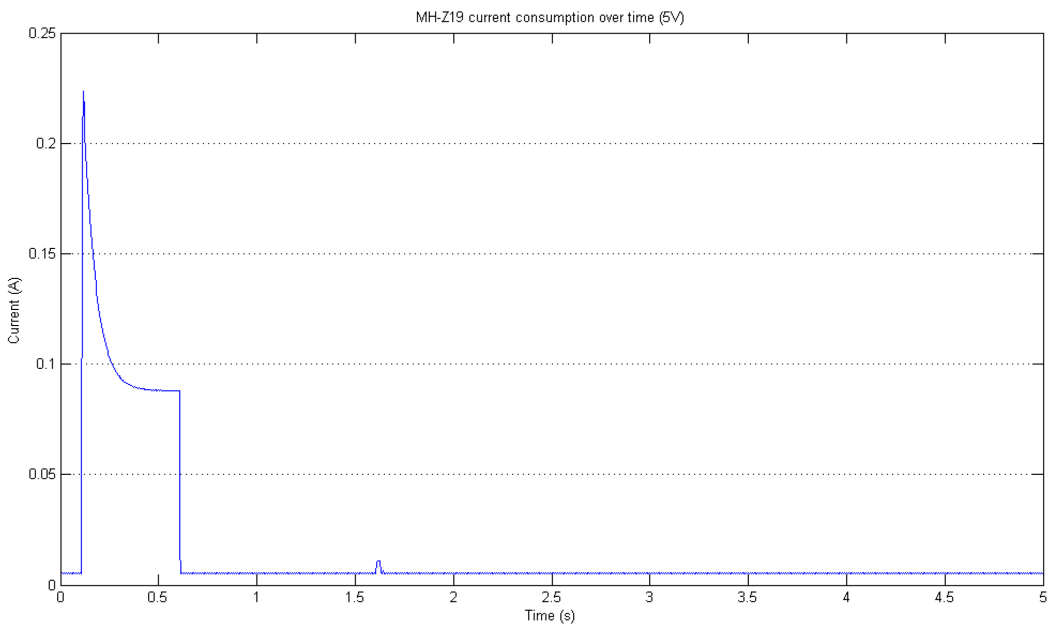
Device	Current measured	Current specified (typ)
AP7361C-33	58 uA	60 uA
SI7020	15 uA	1 uA
BMP085	2 uA	3 uA
MIC2005A	74 uA	80 uA
LM4120AIM5	142 uA	160 uA
LMP91002	4 uA	6.5 uA
STM32L4		
Stop mode	95 uA	100 nA
Sleep mode	291 uA	97 uA
Run mode	18.8 mA	18.1 mA
Vbat (via BAT54C)	5 uA	494 nA
uSD cards		
Sandisk 2GB	64 uA	-
Samsung 4GB	60 uA	-
Mixza 8GB	88 uA	-
WS OLED 1.3" (SH1106)		
Vcc only, sleep	5 uA	<5 uA
Vcc + IO, sleep	22 uA	-
Blank display	20 mA	-
Few lines text	26 mA	-
All white display	46 mA	-

Sensor module measurements

MH-Z19 (CO_2 sensor)

Sensor will take a spike of current every 5 seconds to light the IR lamp. This means a new measurement is only made that often, even if PWM output is 1Hz or datasheet states otherwise.

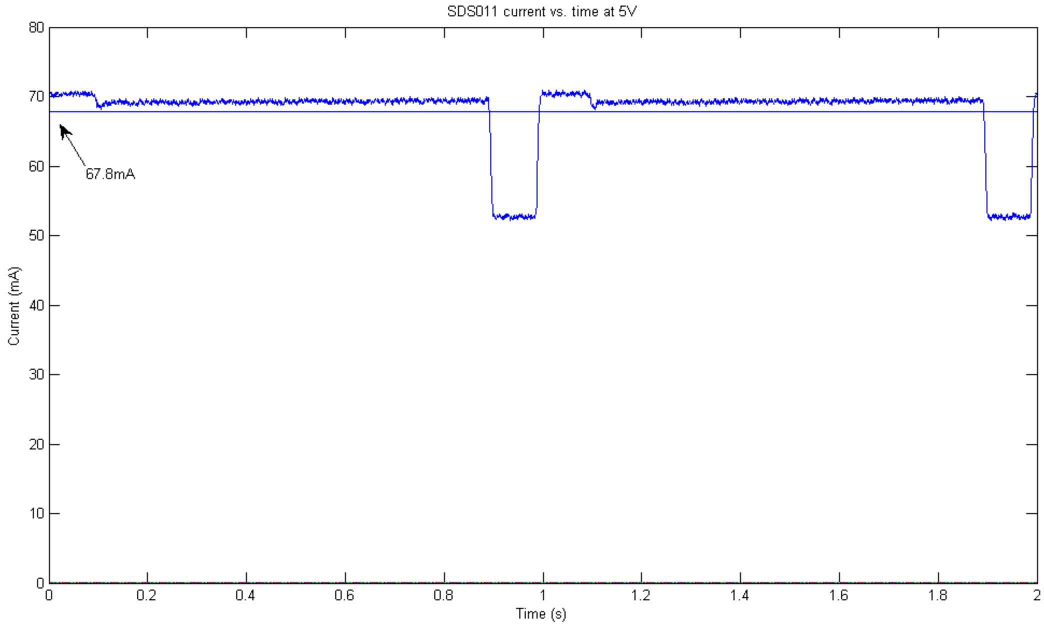
Calculation	Current (mA)	Power (W)
Peak	224	1.12
Average	15.5	0.0775



SDS011 (particulate matter sensor)

Sensor seems to keep laser on majority of the time, and turn off to perform dark sensor calibration. New sensor reading is available every second.

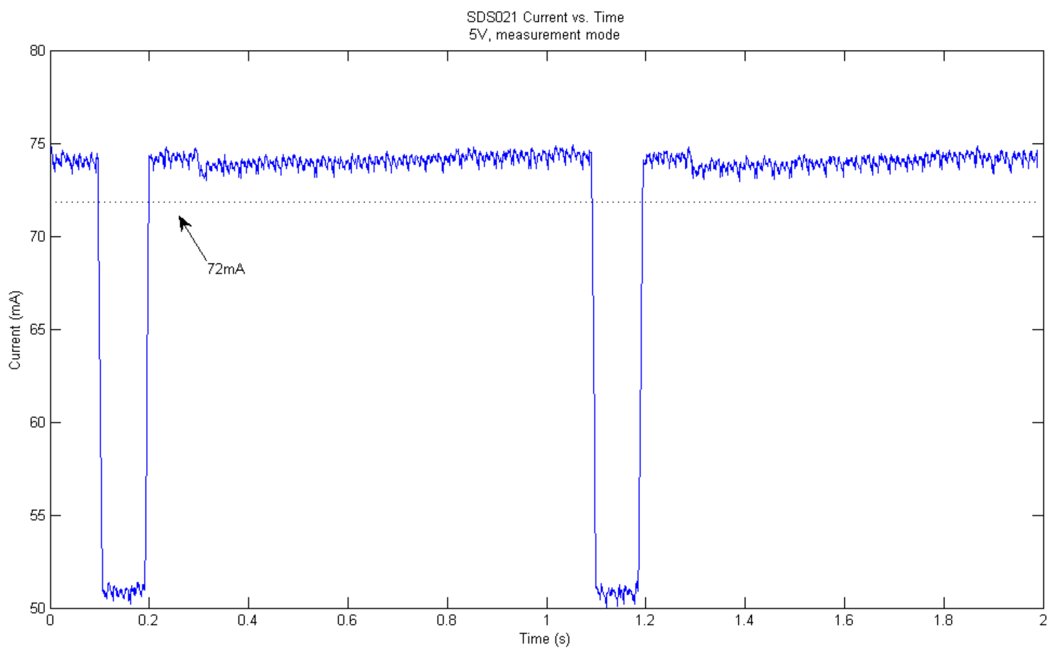
Calculation	Current (mA)	Power (W)
Peak	77	0.385
Average	67.8	0.339
Sleep	3.55	0.0178



SDS021 (particulate matter sensor)

Sensor seems to keep laser on majority of the time, and turn off to perform dark sensor calibration. New sensor reading is available every second.

Calculation	Current (mA)	Power (W)
Peak	75.0	0.375
Average	71.9	0.360
Sleep	2.80	0.014



PMS7003 (particulate matter sensor)

5V supply

Time	Current	Average
3s	38mA	42mA
1s	66mA	

Power supply measurements

No load				
Vin	Vout	Iin (mA)	Iout (mA)	Efficiency (%)
6.0	5.017	1.040	0.000	-
7.0	5.018	0.960	0.000	-
8.0	5.013	1.040	0.000	-
10.0	5.013	0.990	0.000	-
15.0	5.014	0.950	0.000	-

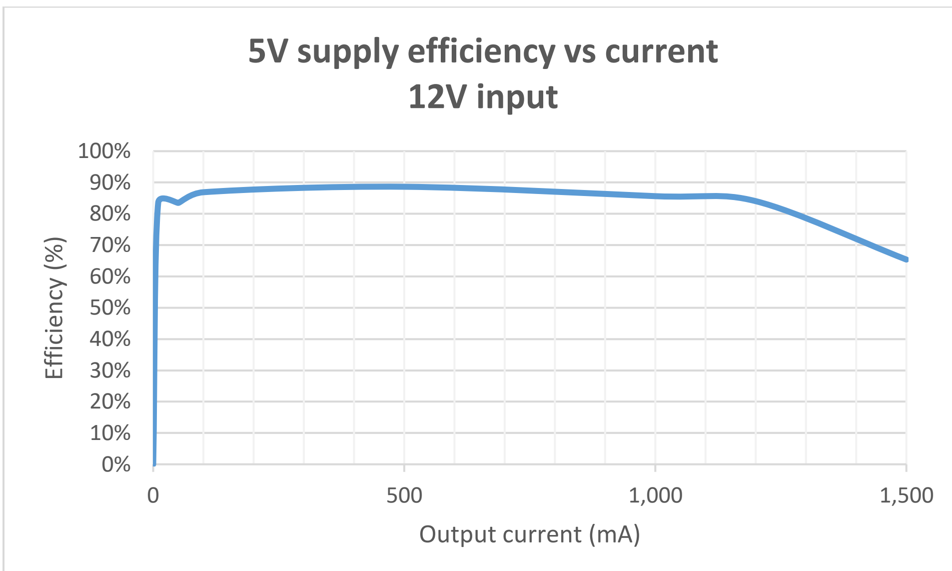
4.56Ω load				
Vin	Vout	Iin (mA)	Iout (mA)	Efficiency (%)
6.0	4.215	728	820	79%
7.0	4.941	846	953	80%
8.0	4.940	725	956	81%
9.0	4.940	635	956	83%
10.0	4.940	564	955	84%
15.0	4.941	366	949	85%

9.83Ω load				
Vin	Vout	Iin (mA)	Iout (mA)	Efficiency (%)
6.0	4.601	392	438	86%
7.0	4.978	388	472	87%
8.0	4.978	338	472	87%
9.0	4.978	299	472	87%
10.0	4.978	269	472	87%
15.0	4.979	181	472	87%

Constant current load (12Vin)				
Vin	Vout	Iin (mA)	Iout (mA)	Efficiency (%)
12.0	5.013	1	0	0%
12.0	5.013	5	10	84%
12.0	5.009	25	50	83%
12.0	5.005	48	100	87%
12.0	4.978	234	500	89%

12.0	4.943	481	1,000	86%
12.0	4.925	586	1,200	84%
12.0	1.470	281	1,500	65%

Constant current load (24Vin)				
Vin	**Vout**	**Iin (mA)**	**Iout (mA)**	**Efficiency (%)**
24.0	5.014	1	0	0%
24.0	5.013	2	10	95%
24.0	5.011	14	50	75%
24.0	5.008	27	100	77%
24.0	4.978	123	500	84%
24.0	4.944	244	1,000	84%
24.0	4.927	294	1,200	84%
24.0	3.330	270	1,500	77%



Noise measurements

- 20MHz BW limit, 12V input

Iout (mA)	Noise (mV RMS)
off	3.80
0	4.30
100	4.50
500	4.60
1,000	4.80