

# THE UNIVERSITY OF NEW SOUTH WALES

SCHOOL OF ELECTRICAL ENGINEERING  
AND TELECOMMUNICATIONS

## Design of a wireless sensorboard for an air pollution monitoring system

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Topic ID: VR24

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**UNSW**  
THE UNIVERSITY OF NEW SOUTH WALES

**Thesis title:**

**Topic number:** VR 24

**Student Name:** Matthew Kelly

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**A. Problem statement**

Air pollution is a serious health issue responsible for an estimated 3.3 million
deaths worldwide per year. On a local scale air pollution costs NSW \$4.7
billion every year in health related expenditures. This suggests a need to
monitor air pollution & track individual exposure. This could be done through
pollution maps with a high spatial resolution, the current air pollution
monitoring systems in Sydney insufficient for this task. The Haze Watch
project aims to produce high resolution pollution map by having a distributed
air pollution sensor network based on a portable air pollution sensorboard.

**B. Objective**

Design and build a wireless sensorboard capable of accurately gathering
pollution data that will be then sent to a laptop. In order to ensure accuracy
testing will be done both in lab conditions and in field testing against a
commercial air pollution monitor.

**C. My solution**

A design of a car mounted wireless sensorboard that uses electrochemical
sensors. The sensorboard sends pollution data via Bluetooth to a laptop for
testing & development purposes in preparation for use with an Android based
application. The laptop uses Matlab to get data from the sensorboard and plot
it in real time as well as well as plots all collected data.

**D. Contributions (at most one per line, most important first)**

Designed and built wireless air pollution sensorboard
Demonstrated correlation with commercial monitor through field testing
Created Matlab program to collect and plot data

**E. Suggestions for future work**

Find better method to secure the sensorboard to vehicles
Use surface mount technology to decrease board size
Integrate sensorboard into other Haze Watch systems

While I may have benefited from discussion with other people, I certify that this thesis is entirely my own work, except where appropriately documented acknowledgements are included.

Signature:  \_\_\_\_\_

Date: 16/10/2012

## Thesis Pointers

List relevant page numbers in the column on the left. Be precise and selective: Don't list all pages of your thesis!

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16	Objective

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15	The Haze Watch project
21	Electrochemical sensors
35	PCB Design

### Method of solution (up to 5 most relevant points)

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26,27	Microcontroller
28-30	Bluetooth & Matlab
31-34	Power Supply
35-40	PCB Design

### Contributions (most important first)

40	Designed and built wireless sensorboard
47-50	Field tested board showing correlation with commercial monitor
30	Created Matlab program for gathering & plotting sensorboard data
	Hypothesised basic equations

### My work

17, 25	System block diagrams/algorithms/equations solved
16	Description of assessment criteria used
47	Description of procedure (e.g. for experiments)

### Results

42-50	Succinct presentation of results
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44-46	J.Liu. (2012)
42,43	S.Yap (2012)
22-25	e2v Design of electronics (2010)
35,36	T.Williams (2008)
10	WHO Air quality & health (2011)

## Abstract

Air pollution is a serious health issue responsible for an estimated 3.3 million deaths per year according to the World Health Organisation. There is also a large financial cost tied to the adverse health impacts caused by air pollution, the NSW Health Department estimating that air pollution costs NSW \$4.7 billion every year in health related expenditures.

This suggests a need to monitor air pollution & track individual exposure. This could be done through pollution maps with a high spatial resolution, the current air pollution monitoring systems in Sydney insufficient for this task because the monitoring stations are limited in number across a vast area. In order to achieve air pollution monitoring at a higher resolution new system needs to be devised.

The Haze Watch project aims to produce a high resolution pollution map by having a crowd sourced air pollution sensor network that is comprised of four parts, a wireless sensorboard, users equipped with smartphone, a server for storing sensor data and applications which will use that data to generate interpolation maps of pollution.

This thesis is focused on designing and building a wireless sensorboard capable of accurately gathering pollution data then sending it via Bluetooth to a laptop (for development purposes) in preparation for an Android smartphone based application. The main pollutants observed through this thesis are carbon monoxide (CO) and nitrogen dioxide (NO<sub>2</sub>).

Throughout this thesis I have worked on designing a sensorboard starting a gas sensor circuit, leading into a working breadboard prototype then finally a full PCB implementation of the wireless sensorboard. Lab conditions testing of the breadboard prototype has shown promising results with the accuracy of the sensorboard almost identical to a commercial gas monitor. Field testing has shown that the sensorboard is relatively accurate and more sensitive at lower gas concentrations than the commercial gas monitor however there are some short term discrepancies in terms of reading amplitude & reaction speed between the two devices due to effects from air flow. These effects should be negligible over a longer duration average however.

With the PCB implementation of the wireless sensorboard finished and the accuracy shown to correlate well with a commercial meter it, the wireless sensorboard is ready for integration with other existing and upcoming Haze Watch systems. With the full system implemented it will make high resolution air pollution mapping possible, allowing people to manage their exposure to air pollution and putting us a step forward in controlling air pollution.

## **Acknowledgements**

I would like to thank the members of the Haze Watch project both past and present, especially Shern Yap and Judy Liu for all their work in the testing and calibration of the sensorboard. I would also like to thank my supervisor, Dr. Vijay Sivaraman, for his guidance and support as well as for actively encouraging us throughout the project.

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# 1 Introduction

Air pollution is a worldwide issue linked to several respiratory & cardiovascular illnesses such as lung cancer and heart disease. According to the World Health Organisation air pollution is estimated to be the cause of 3.3 million deaths per year, with urban outdoor air pollution estimated to be responsible for 1.3 million of those deaths[24]. On a local scale the adverse effects of air pollution are also apparent. The New South Wales Health department estimates that 2.3% of all deaths per year in Australia are a result of air pollution. They estimate that air pollution costs NSW \$4.7 billion dollars per year in health related expenditures[17].

In order to identify risk areas of pollutants and gauge personal exposure to air pollution, there is a need for an air pollution monitoring system that is able to effectively map air pollution levels at a high spatial resolution as well as estimate personal exposure. The present air monitoring system has only 14 active stationary sites spread over the entire Sydney metropolitan area. This is insufficient for mapping air pollution at a high spatial resolution and for monitoring personal pollution exposure as these points separated over tens of kilometers cannot reflect the actual pollution concentrations between sites.

The Haze Watch project aims to develop a crowd sourced distributed air pollution sensor network. Participants in the project will be given an wireless sensorboard that can sample air pollution concentrations then send the pollution data to a server which can utilise the data to track personal exposure and generate an air pollution map.

The objective of this thesis is to design the portable air pollution sensorboard as part of the Haze Watch project. The air pollution sensorboard will obtain a sensor reading, process it and then send it to a laptop in preparation for a platform with both space-time stamping capabilities and mobile internet access, such as a smart-phone.

## 2 Background theory

### 2.1 Air pollution

According to the NSW Dept. of Health[17] and the World Health Organisation[24] there are six major health risk pollutants to be concerned about in air pollution. Below are details regarding the health risks the pollutants pose, where they originate from and the gases chosen as the focus of this thesis.

- Particulate Matter <10um (PM10) - Coarse particles of size between 2.5um and 10um resulting from vehicle/industry emissions and wood fires. Particles of this size are small enough to settle deep into lungs in areas such as the bronchioles or alveoli. PM10 aggravates respiratory & cardiovascular illnesses and can cause coughing. It also irritates eye & mucus membranes.
- Particulate Matter <2.5um (PM2.5) - Fine particles of size less than 2.5um. Similar to PM10 however due to their small size they pose a greater risk to respiratory and cardiovascular systems, able to be penetrate into the gas exchange region of the lungs, PM2.5 is able to get into the bloodstream and affect other organs.
- Carbon Monoxide (CO) - A colourless, odourless gas caused by incomplete combustion of carbon in fuels. The primary source of this gas is from vehicle emissions, especially during a cold start as catalytic converters which reduce CO emissions need a warm up period to function correctly, and during cold weather (lower temperatures means increased likelihood of incomplete combustion). CO combines with hemoglobin in the bloodstream to form carboxyhemoglobin, reducing the oxygen reaching organs and tissue. In low concentrations and exposure this results in headaches & dizziness, in higher concentrations and exposure CO poisoning can lead to neurological damage and death.
- Nitrogen Dioxide (NO2) - A brown gas caused by fuel combustion, visibly brown at high concentrations. Unlike CO it is increased by higher temperatures during combustion and has been on the rise since higher temperature combustion has been equated with better fuel efficiency. NO2 Irritates respiratory systems and makes asthmatics susceptible to lung infections and asthma attacks.
- Ozone (O3) - Ozone occurs at ground level from a reaction of sunlight and vehicle/industry emissions. Peak periods for this pollutant occur in summer after mid-day due to the increased levels of sunlight and vehicle activity during the day. Ground level ozone is an irritant that narrows airways, causes coughing and chest pain, aggravates respiratory illnesses such as asthma and damages lung cells.
- Sulfur Dioxide (SO2) - Colourless gas with sharp odour that occurs from burning of fossil fuels. It primarily affects the respiratory system, causing inflammation of the lungs as well as aggravating asthma & bronchitis conditions, increasing risk of infection. It's also linked to cardiovascular problems and can cause eye irritation on contact.

### 2.1.1 Air pollution sources

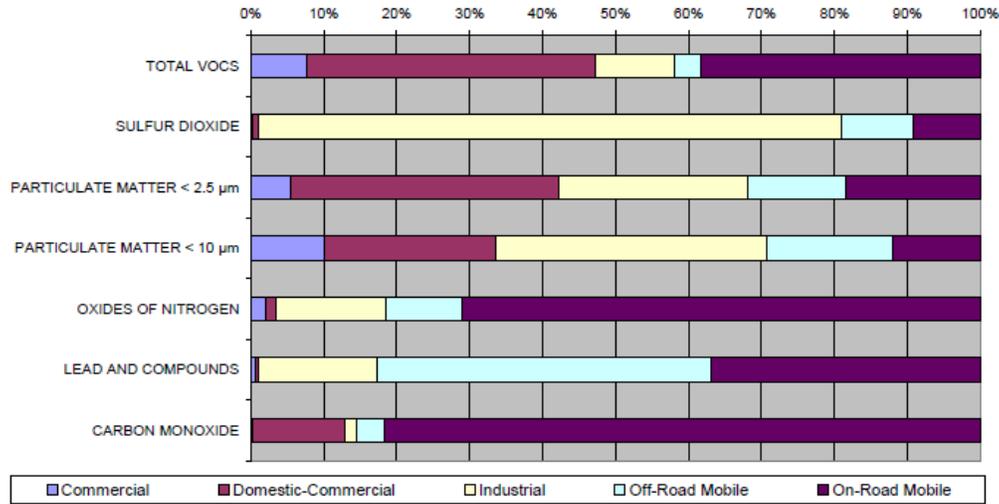


Figure 1: Composition of human caused pollution within the Sydney region[8]

Figure 1 summarises the major air pollutants and their sources in the Sydney region. It can be seen from the chart that the most significant sources of pollution are off-road & on-road vehicles as represented by the aqua and purple coloured bars on the graph, furthermore nitrogen oxides (NOX) and carbon monoxide (CO) appear to be the most prolific pollutants from vehicles.

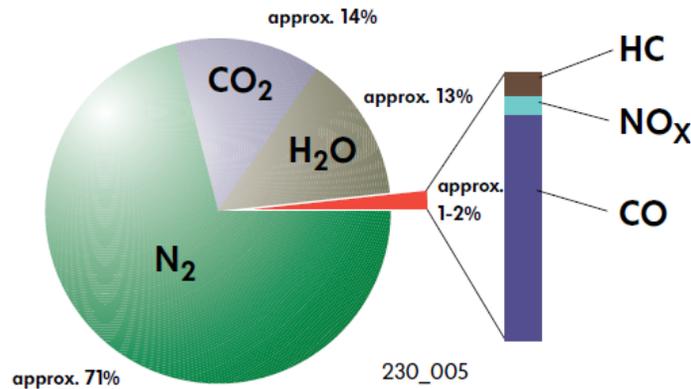


Figure 2: Composition of exhaust emissions of petrol engines[20]

Examining figure 2 from Volkswagen it can be determined that (in petrol combustion engines) the two most prominent pollutants are NOX and CO. The final goal is to have the sensor board mountable on a car; NOX and CO are the most prevalent pollutant types from car emissions in Sydney this suggests that the best way of measuring pollution overall is to measure oxides of nitrogen and carbon monoxide.

### 2.1.2 Pollutant choices

Carbon monoxide (CO) and nitrogen dioxide (NO<sub>2</sub>) as the primary pollutants to investigate for the following design reasons:

- Simple to source - Dourcing CO & NO<sub>2</sub> gas for testing the sensorboard only requires access to a car as according to figures 1 and 2 they are the most prominent gasses in car exhaust, lowering the need to find chemical based gas generation methods for testing. NO<sub>2</sub> is chosen as the nitrous oxide to use as NO can be difficult to measure, combining with oxygen in the air to become NO<sub>2</sub>.
- Simple to test - Getting results for field testing could be as simple as walking next to a busy road or driving a car around because of the amount of CO and NO<sub>2</sub> that is output from vehicles.
- Safety - Considering CO combines with oxygen in the air to form CO<sub>2</sub>, NO<sub>2</sub> is visible to the naked eye in high concentration and that modern car engines should produce far below any unsafe limits we should be able to source both gasses in relatively safe concentrations from car exhaust resulting in less risk of harm when testing.

### 2.1.3 Safety considerations

Hazardous thresholds were found to ensure that during testing there was minimal risk to health from gas exposure and that any CO & NO<sub>2</sub> produced for testing remains within safe exposure limits. In the tables below two groups dictating safe limits on gas concentrations included the Occupational Safety and Health Administration (OSHA) and the National Institute for Occupational Safety and Health (NIOSH).

CO Concentration (PPM)	Health hazards & symptoms
35	OSHA recommended 8 hour exposure limit
50	OSHA Permissible 8 hour exposure limit
100	OSHA Exposure limit to remove employees from enclosed spaces
200	Mild headaches, dizziness & nausea after 2-3 hours
400	Frontal headache in 1-2 hours, Life threatening after 3 hours
1500	Headaches, dizziness & nausea after 30 mins, death within 1 hour

Table 1: Carbon monoxide hazards & symptoms[4]

NO <sub>2</sub> Concentration (PPM)	Health hazard & symptoms
1	NIOSH recommended 8 hour exposure limit
5	OSHA permissible 8 hour exposure limit
25	Respiratory irritation and chest pains within an hour
50	Eye irritation, pulmonary edema and lung lesions after 1 hour
100	Coughing, pulmonary edema & death after 1 hour
250	Coughing, pulmonary edema & death within 1-2 hours

Table 2: Nitrogen dioxide hazards & symptoms[16, 1]

## 2.2 Pollution monitoring

### 2.2.1 Current air pollution monitoring systems in Sydney



Figure 3: Air monitoring stations in the Sydney area[7]

Looking at the current system for air pollution monitoring in Sydney there are 14 active stations as shown on figure 3. Sites also have to take into consideration placement based off the The Australian/New Zealand Standard for air pollution monitoring sites[15], the shortcomings of the existing system are as follows:

- Air flow effects: Sites should not be placed near walls, buildings or trees that impede airflow.
- Chemical interference: Sites should not be near where vehicle/industrial emissions could interfere with measurements.
- Electrical interference: Sites need to take into account over-head power lines affecting sampling equipment.
- No human disturbances: Sites should have no activity near the site such as construction or demolition as it could affecting readings.
- Power and telecommunications infrastructure: The site will need constant power and data transmission capabilities.

The above shortcomings coupled with the large spread between stations and the low number of stations imply that the placement of the air monitoring sites are intended for measuring the pollution concentration over a large area ignoring localised concentrations within small areas. This shows that the current air pollution monitoring system isn't suitable for the aims of high spatial resolution pollution mapping, nor is it suitable for gauging personal exposure.

## 2.2.2 Portable air pollution sensors



Figure 4: The GasAlertMicro 5 portable air pollution monitor

Portable air pollution monitors are currently available such as the commercial gas monitor used as a benchmark in this thesis, the GasAlertMicro 5, however at a prohibitive cost of over \$1000 per unit and with no bluetooth functionality to connect to a smartphone it cannot be used as part of our air pollution monitoring network.

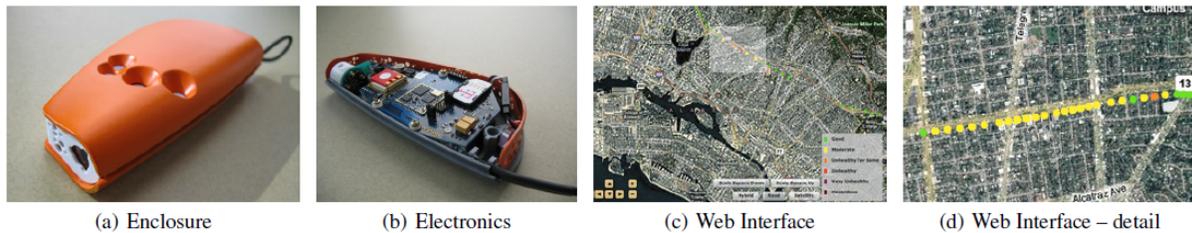


Figure 5: The Common Sense project: Participatory Urban Sensing Using a Network of Handheld Air Quality Monitors[10]

One existing project that's similar to what the Haze Watch project is trying to achieve is the Common Sense project developed by the Computer Science Division at the University of Berkeley. The Common Sense project monitors air pollution using a standalone pollution sensorboard capable of acquiring data from electrochemical gas sensors, applying a space-time stamp through an onboard real time clock & GPS module then sending that data to a server using an onboard GPRS radio module. Data on the server pollution visualisation maps are formed via an online web interface, as shown in figure 5 (c) and (d). Despite the promising articles of this project there are no published results and no indication of the projects continuation after 2010.

### 3 The Haze Watch project

The lack of current distributed air pollution sensor networks is one of the driving factors behind the Haze Watch project, aimed at producing a high resolution pollution map by having a crowd sourced air pollution sensor network, furthermore the lack of any available off the shelf portable pollution sensors that can communicate to a mobile internet equipped platform is the driving factor behind this thesis.

#### 3.1 Project overview

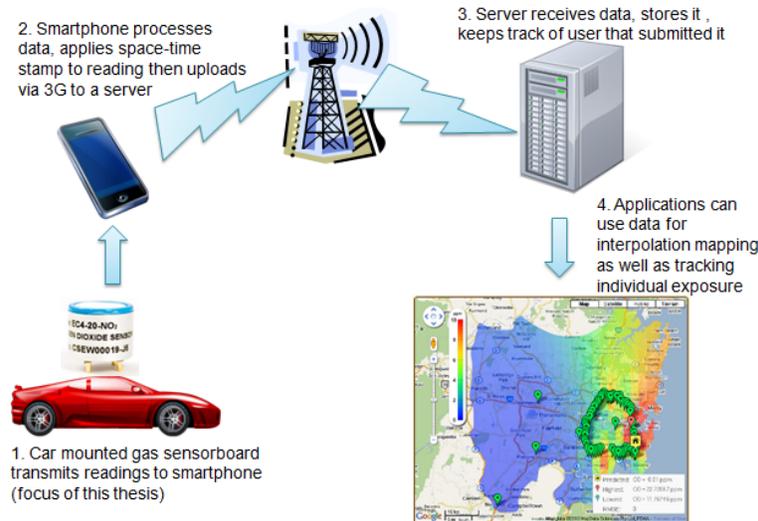


Figure 6: The Haze Watch project - graphical overview

The Haze Watch project can be divided into the following sections:

1. Car mounted gas sensorboard - The focus of this thesis. A car is considered an ideal platform for the sensorboard as it can travel a far range in a short amount of time, collecting many data points over a wide area and also giving users sensor feedback on personal air pollution exposure. The sensor readings will then be transmitted to a platform such as a smart phone via bluetooth.
2. Smart phone - The smart phone will apply a space-time stamp using it's GPS module and real time clock, it will then send the data to a central server. Using a standalone unit would require mobile internet modules & ongoing data subscriptions, equating to an increased cost and complexity of the device. As approximately 46% of all Australians own a smartphones as of 2011[19] most users will already have GPS and mobile internet capabilities, making mobile internet modules redundant.
3. Server - A server will receive and store the data for use in other applications. In order to make the wireless sensorboard more user friendly, the calibration constants required to scale pollution readings to the correct values will be stored server side. This means the microcontroller shouldn't need to be reprogrammed between sensorboard recalibrations.
4. Applications - Applications will be able to use the data to generate real time pollution map (such as the 2010 Haze Watch map featured on figure 6) & track personal exposure to pollutants.

## **3.2 Previous work**

The Haze Watch project was started in 2010 by a thesis group under the supervision of Dr Vijay Sivaraman. The group had implemented the main systems of the Haze Watch project including a sensor board equipped with metal-oxide sensors, a smart phone application capable of both displaying readings to users and transferring data from sensor to server, finally a server was setup so an application based off google maps could generate interpolation maps of the pollution readings.

In 2011 another thesis group began working on the Haze Watch project with a focus on improving the software side of the project (programming the microcontroller, smart phone app and interpolation maps). Both groups had problems with the performance and accuracy of the metal oxide sensor board, resulting in the exploration of alternatives to metal oxide sensors.

## **3.3 The aim of this thesis**

My aim for this thesis is to design and build a wireless sensorboard capable of accurately gathering pollution data through the use of electrochemical sensors that can send the data via Bluetooth to a laptop for testing & development purposes in preparation for use with an Android based application.

## 4 Sensorboard design overview

### 4.1 Top level design of sensorboard

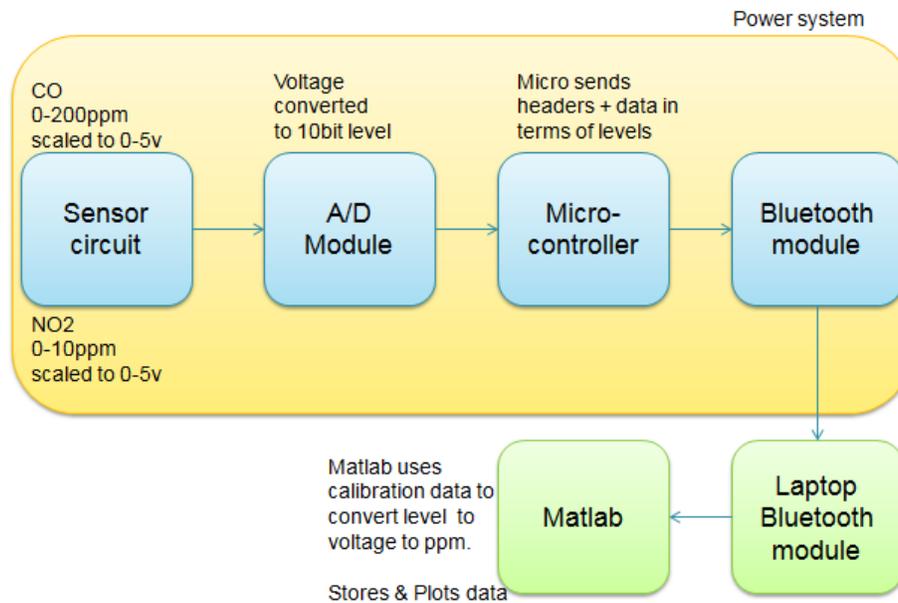


Figure 7: Top level design for sensor board

This is the top level design of the sensorboard that aims at showing the major components of the sensorboard design, the sensorboard design blocks in blue, the power system in yellow and the components external to the sensorboard in green. Designing of the sensorboard focused around breadboard implementable dual inline pin (DIP) components in order to prove a working prototype before PCB production.

## 4.2 Description of equipment required for thesis work

### 4.2.1 Sensorboard circuit testing

- Gas testing chamber - Sealed perspex chamber with enough space for equipment such as a voltmeter, electric fan to mix gasses, breadboard & commercial meter.
- Commercial gas monitor - We used the Gas Alert Micro 5 as a benchmark to test how accurate our circuit is.
- Voltmeter - Initially used to check voltage out of the gas sensor circuit, this was abandoned for matlab once the full circuit was working as testing could be automated.
- Variable dual power supply - Providing power while testing in lieu of batteries.
- Oscilloscope, Voltmeter, Signal generator - Used for testing breadboard circuit parameters such as correct quantisation.
- Microcontroller programmer kit - programming the microcontroller.
- Laptop equipped with bluetooth & Matlab - for developing the board quickly and collecting data.
- Power drill - Used for drilling mounting and ventilation holes on the PCB enclosure.

### 4.2.2 PCB Manufacturing

- Electronics components - Breadboards, PCB's, resistors, capacitors, bluetooth modules & IC's.
- Soldering station - For electrical work and PCB stage assembly.
- Scalpel - Track cutting in the first sensorboard PCB
- Plastic nipper - Cutting leads of passive components post-soldering

### 4.2.3 Software

- MPLAB IDE v.8.46 - An IDE for programming Microchip microcontrollers. Along with HI-TECH C compiler allows programming of microcontroller in C
- Matlab v7.12.0 - Used as a platform for storing and displaying sensor board data.
- Eagle CAD - Electronics CAD tool for circuit schematic & PCB design. With the Eagle 3D addon allows 3D visualisation of a populated PCB.
- Presentation & report writing software - Microsoft Powerpoint, Lyx  $\text{\LaTeX}$  word processor, CutePDF, pdfbinder.

### **4.3 Summary of design stages & results**

Below is a chronological list of the stages that the design of the sensorboard went through, focusing on the aims in order to get that particular stage of the sensorboard operating as well as results from those stages. Full detailed designs will be given in subsequent sections.

#### **4.3.1 Stage 1 - Gas sensor circuit**

- Aim: Design a gas sensor circuit for the chosen electrochemical sensors and test output voltage when target gas is input against predicted values.
- Results: Worked with Melbourne University research student, Shern Yap, to show gasses fell within predicted values and results were linear.

#### **4.3.2 Stage 2 - Microcontroller**

- Aim: Program microcontroller and analogue to digital module to take in test voltage (controlled by variable resistor) and show A/D module works on upper 4 bits of LEDs by counting up in binary.
- Results: Demonstrated microcontroller and A/D module working through output bits counting up and down corresponding to potentiometer output, proving the digital portion of the sensorboard was operating correctly.

#### **4.3.3 Stage 3 - Bluetooth + Matlab**

- Aim: Connect microcontroller to matlab via bluetooth module. Input test voltage from a signal generator to the A/D module. Plot and scale data to obtain the same wave form.
- Results: Connected sensorboard to Matlab. A sawtooth wave on the signal generator resulted in a sawtooth wave being plotted in matlab. This showed correct operation of the digital & matlab.

#### **4.3.4 Stage 4 - Breadboard implementation & testing**

- Aim: Connect gas sensor circuit to the A/D module creating full implementation of the sensorboard. Obtain plot in matlab of accuracy through testing against a commercial gas monitor.
- Results: Worked with UNSW thesis B student Judy Liu to show a correlation between commercial gas monitor output and our circuit output.

#### **4.3.5 Stage 5 - PCB design & Unit construction**

- Aim: Go from breadboard design to PCB design, incorporating an enclosure and mounting onto a vehicle.
- Results: Designed PCB and constructed operational sensorboard.

#### **4.3.6 Stage 6 - Field testing**

- Aim: Drive the finished unit around a route and compare against the commercial meter.
- Results: Demonstrated a strong correlation between the results of sensorboard unit and the commercial meter.

## 5 Gas sensor circuit

The gas sensor circuit is the core function of the sensorboard, designed to measure the gas concentration and output a voltage proportional to the amount of gas measured in parts per million by volume (ppm).

### 5.1 Gas Sensor technologies

The two main gas sensor technologies I'll be examining are metal oxide sensors and electrochemical sensors.

#### 5.1.1 Metal oxide sensors

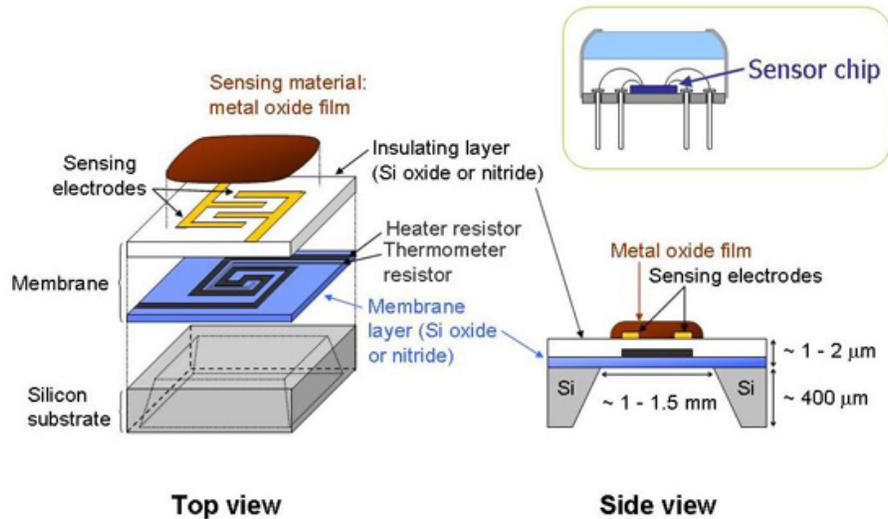


Figure 8: Metal oxide sensor internal view[9]

Metal oxide sensors have been trialed before by the 2010 and 2011 Haze Watch groups with varying success, the main problem being the difficulty in getting accurate results as the sensor is non-linear.

Metal oxide sensors operate by having a sensing layer of metal oxide which is first heated by a heating element. This layer is placed between two electrodes. Once the sensing layer has been heated sufficiently the device can begin operation. If gas of the sensor's type falls on the surface of the sensing layer then the resistance of the metal oxide layer changes. This change in resistance can be read as a change in voltage.

While the metal oxide sensors are low cost at around \$5 to \$10 each, they are not ideal due to the vulnerability of the sensor to many external effects. Their operation combines electrical, chemical & thermal effects. In terms of electrical issues there's electrical noise, quantisation and non-idealities in circuit components. In terms of chemical effects humidity, cross sensitivity and even poisoning<sup>1</sup> of the metal oxide layer can occur. In terms of thermal effects ambient temperature and even airflow will alter the accuracy. All these effects means it's difficult to calibrate the sensors and ensure their accuracy.

<sup>1</sup>gas particles cling to the surface of the sensor, permanently changing its operation

### 5.1.2 Electrochemical sensors

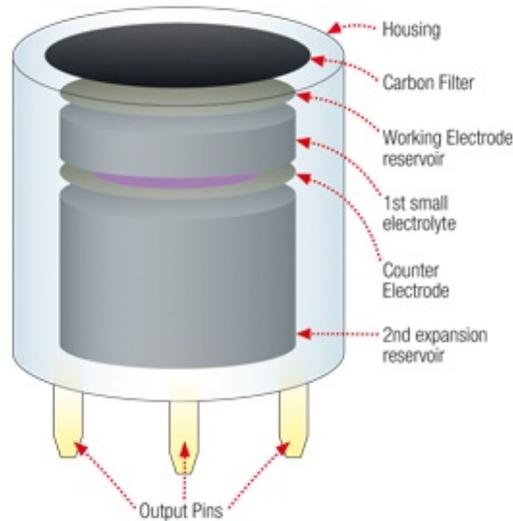


Figure 9: Electrochemical sensor internal view[12]

Electrochemical sensors are what I have used for this thesis as they are more accurate than metal oxide sensors. The way they operate is to have the gas they target oxidised at the surface of the working electrode. This chemical reaction causes a current proportional to the gas concentration to flow into or out of the working electrode. The counter electrode acts as an electrical return path to this current and the reference electrode helps to keep the working electrode biased at a particular voltage.

Electrochemical sensors are much more expensive than the metal oxide units, each sensor priced at \$50-\$100 depending on the sensor type. The biggest advantage of electrochemical sensors is the accuracy they provide and low vulnerability to external effects, with a permeable membrane or filter blocking out some effects of cross sensitivity<sup>2</sup> and air flow. This makes it easier to obtain accurate data as current out of the sensor is proportional to gas concentration in while external factors such as temperature and pressure can (for the most part) be compensated for or neglected, in this respect the devices are linear and can be represented in the form  $y = mx + b$  where  $y$  is output ppm,  $m$  based off is the sensitivity of the sensor (needs to be worked out from calibration testing),  $x$  is the current output and  $b$  is an offset current from the sensor.

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<sup>2</sup>non-target gasses affecting readings for targeted gas

## 5.2 Gas sensor specifications

Specification	EC4-500-CO	EC4-20-NO2
Range	0-500ppm	0-20ppm
Sensitivity	55-85nA/ppm CO	-(450-750)nA/ppm NO2
Zero in air	<+/- 3.1ppm CO	<0.9ppm NO2
Resolution	1ppm CO	0.1ppm NO2
Long-term output drift	<2% signal/month	<2% signal/month
Storage life	6 months	6 months
Applied bias(Vsense-Vref)	0V	0V
Output voltage polarity	Positive	Negative

Table 3: Gas sensor specifications

The above data was obtained from the datasheets of the chosen gas sensor manufacturer, e2v, and were important in designing the circuit. The range & resolution given here give a good indication about the number of different levels we'll need to be able to quantise to on the A/D module, 500 different values for CO and 200 different values for NO2. By amplifying the output voltage it's possible to spread out this number of values at the cost of capping out earlier reducing range, i.e. restrict the range to 250ppm but the resolution becomes 0.5ppm.

The sensitivity relates back to the linearity discussed before. By working out the sensitivity and offset for each sensor the ppm value can be worked out based off the current output of the sensor. The zero in air test<sup>3</sup> gave a good indicator of correct operation when just turning the device on. Any deviation from this zero meant that the device needed time to stabilise it's biasing which could take up to a few hours, destabilisation caused by incorrect circuit connections, shorting of the sensor pins to each other or even lack of use. This results in a shift of a few PPM from the zero. Because of this the circuit should be designed to always have power to the gas sensor circuit even with the digital parts of the sensorboard switched off.

Construction and use had to be considered for both sensors. On the datasheets it's stated that soldering would damage the sensor warranty, as such sockets would need to be used so that sensors could be plugged in and out without use of soldering. Looking at the long-term output drift and storage life of the sensors each sensor should be recalibrated every 6 months as the sensor becomes inaccurate.

A consideration for the sensors is temperature. As temperature changes the current offset of the sensor will be affected by a small amount. The datasheets of both sensors contain plots which dictate ppm offset vs. temperature and sensitivity vs. temperature. This is important for calibrations as temperature could cause a small change in the sensitivity and offset values.

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<sup>3</sup>Lab conditions in air should give close to 0ppm, if not close to 0ppm some time might be needed for the sensor to stabilise

## 5.3 Sensor circuit design

### 5.3.1 Designing the circuit

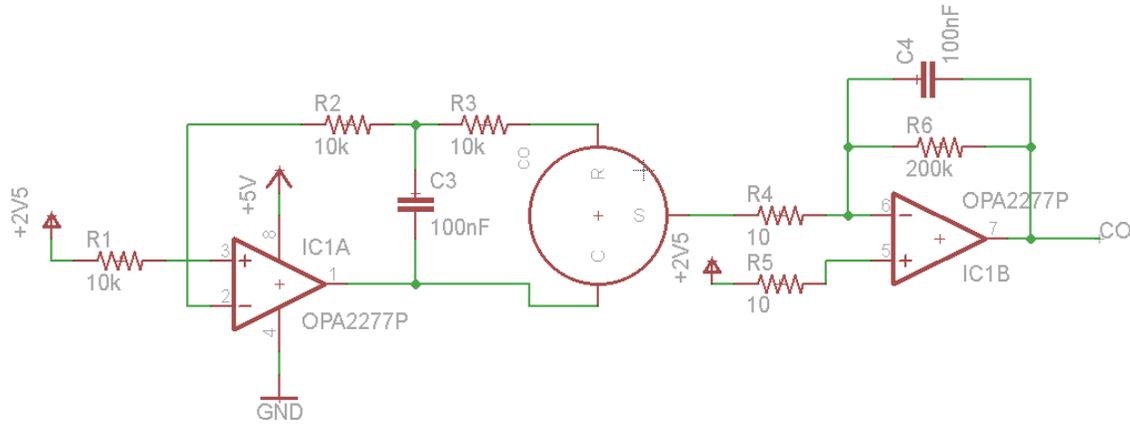


Figure 10: Gas sensor circuit for CO

The current circuit that's being used for the gas sensor is based on one of the examples given by the sensor manufacturer e2v[2]. This circuit is designed to work on a single power rail, and in the 10 the circuit runs on 5v power rails using half the rail voltage as a reference voltage/virtual ground (2.5v). The large circle in the center is the gas sensor with pins labeled as follows: C - Counter electrode, S - Sensing/Working electrode, R - Reference electrode. The circuit left of the sensor is the biasing part of the circuit, because the bias voltage is 0v for both CO and NO<sub>2</sub> sensors<sup>3</sup> the voltage into the positive terminal of the opamp should be 2.5V when there is zero CO and NO<sub>2</sub> apparent. In the presence of CO the output should go towards 5v and in the presence of NO<sub>2</sub> the output should go towards 0v.

The right hand side of the gas sensor circuit is the transimpedance amplifier, it turns the current output from the sensor into a voltage at the output of the OPAMP based off the gain resistor value(R6, 200k ohm here). This can then be read into a microcontroller via an A/D module. As in<sup>3</sup> the output at the voltage is listed.

### 5.3.2 Design choices

According to the e2v 'Design of electronics for EC sensors' sheet operational amplifier choice should fulfill the following parameters:

In order to develop the circuit on a breadboard a dual inline package (DIP) needed to be used. The cheapest solution found was the OPA2277P dual OPAMP at about \$15 per unit. While not cheap the package includes two OPAMPs which allows one OPA2277P to be used for both the biasing and transimpedance sections of the gas sensor circuit. A cheaper \$5 alternative, the OPA2277PA, did not meet the desired parameters above but appeared to perform similarly. Surface mount technology (SMT) equivalent OPAMPs also appeared cheaper and could be considered for future development.

Passive components have been chosen to have less than 1% tolerance, this is most important for the gain resistor as it will affect the accuracy of the circuit. I have chosen the gain resistor to be 200k for CO and 402k for NO<sub>2</sub>, this will restrict the range of pollutants able to be seen at the output of the resistor but will improve resolution at lower gas concentrations. From previous testing by the 2010 Haze Watch group and from testing the commercial gas sensor, normal on-road CO concentrations should be below 5ppm while in tunnels it should be less than 100ppm. On average CO's range should be about 178ppm (assuming sensor sensitivity of 70nA/ppm) and NO<sub>2</sub>'s range should be about 10ppm (assuming sensor sensitivity of 600nA/ppm).

For supply rails voltage the two low voltage standard choices are 5v and 3.3v, I have chosen 5v for quantisation concerns which will be expanded upon in the microcontroller and A/D section.

Parameter	Value
Input bias current	<5nA
Input offset voltage	<100uV
Output voltage swing	Rail to rail ideally

Table 4: Recommended OPAMP parameters

### 5.3.3 Circuit formulae

Formula	Description
$V = IR$	Ohms law
$V_{out} - V_{ref} = I_{sensor} * R_{gain}$	Output voltage
$I_{sensor} = (S_{sensor} * ppm_{gas}) + I_{offset}$	Sensor current
$V_{out} = R_{gain}[(S_{sensor} * ppm_{gas}) + I_{offset}] + V_{ref}$	Calibration equation
$ppm_{gas} = \frac{1}{S_{sensor}} \left( \frac{V_{out} - V_{ref}}{R_{gain}} - I_{offset} \right)$	PPM equation
$ppm_{max} = \frac{1}{S_{sensor}} \left( \frac{V_{cc} - V_{ref}}{R_{gain}} \right)$	PPM range equation
$resolution = \frac{ppm_{max}}{2^{n-1}}$	Resolution equation

Table 5: Gas sensor circuit equations

The above table outlines the equations used to characterise the gas sensor circuit. Ohms law can be applied to the transimpedance amplifier such that the output voltage of the transimpedance amplifier is equal to the current out of the sensor multiplied by the gain resistor. The sensor output current is based off the sensitivity ( $S_{sensor}$ ) of the sensor in nano-amps per ppm of gas (nA/ppm), based off the datasheets for the e2v sensors this value should be from 65-85nA/ppm for CO and 450-750nA/ppm for NO2. The current output is equal to the sensitivity (nA/ppm) multiplied by the gas concentration (ppm) plus an additional current offset. These calibration constants made up of the sensitivity and offset were able to be found through calibration testing.

By arranging the output voltage and sensor current formulas we can obtain the calibration formula.  $V_{out}$ ,  $V_{ref}$  and  $R_{gain}$  are constants set in the design. PPM of the gas is unknown but can be compared against a commercial gas meter to be found. In this way the formula is in the form of  $y=mx+b$  where  $y$  is the voltage read from the circuit,  $m$  is the sensitivity,  $x$  is the gas concentration and  $b$  is the offset (ignoring constants), both sensitivity and offset can be found by plotting  $V_{out}$  vs PPM. With a sensor's sensitivity and offset known the gas sensor circuit output voltage can be translated into a gas concentration with the PPM equation

The range equation shows the approximate maximum PPM value before the gas sensor circuit reaches supply rails voltage, i.e. the range of gas concentrations which the circuit can read. It was also used when choosing an gain resistor to ensure the value chosen keeps the PPM within an acceptable range.

The resolution equation shows the PPM difference between adjacent quantisation levels and highlights the accuracy of the gas sensor circuit. The equation divides the maximum ppm value by half the A/D quantisation levels where 'n' is the bit resolution of the A/D module. For example with a 10bit A/D and the estimated range of 178ppm the difference between quantisation levels is 0.348ppm, i.e. the actual ppm is within 0.348ppm of the current reading. In order to increase resolution & accuracy without trading off range the best solution would be to increase the A/D module resolution.

Power supply must also be considered in resolution. While the resolution & range can be kept the same by adjusting  $R_{gain}$  proportionally to  $V_{cc}$ , as  $V_{cc}$  is decreased the voltage between levels also decreases. For example using a 10 bit A/D with 5v gives 4.88mV/level while using 3.3v would give 3.22mV/level. Power supply ripple caused by the digital part of the circuit, including the microcontroller and Bluetooth module, could cause the quantised level to shift around the actual value. In order to reduce this it's better to use the larger supply voltage of 5v.

## 6 Microcontroller

The microcontroller is at the heart of the sensorboard, interfacing with the gas sensor circuit via an analogue to digital (A/D) module and the Bluetooth module through a UART module. The main task of the microcontroller is to grab the quantised voltage from the A/D module then send it to the laptop via a Bluetooth module.

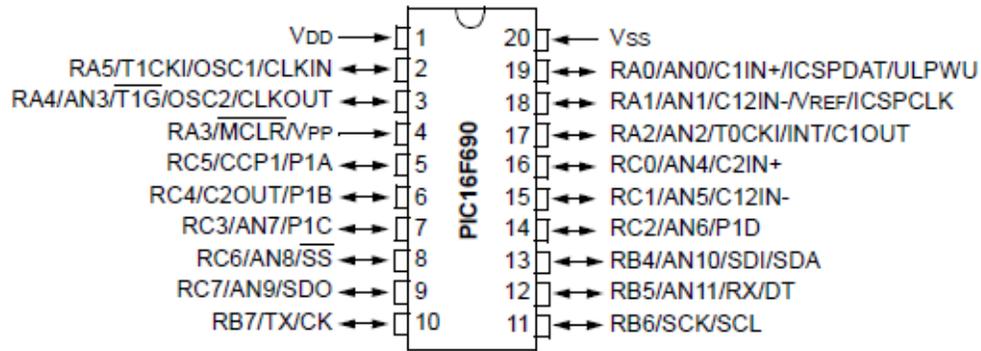


Figure 11: PIC16F690 pin diagram

The microcontroller I've chosen to use is the PIC16F690 as I have previous experience with the PICKit 2 Demoboard. The PIC16F690 also comes equipped with an onboard 10-bit A/D module and can communicate with the Bluetooth module through it's Enhanced Universal Synchronous Asynchronous Receiver Transmitter (EUSART) module.

Coding for the microcontroller was done in MPLAB IDE using the HI-TECH C compiler, allowing programming to be done in C and the writing .



Figure 12: PICKit 2 demoboard and programmer

## 6.1 A/D module

The voltage from the gas sensor circuit is turned into to an equivalent digital level through an A/D module. I've chosen to use the onboard A/D module as it has extensive documentation, is simple to use and with all 10 bits is sufficient for quantising CO data.

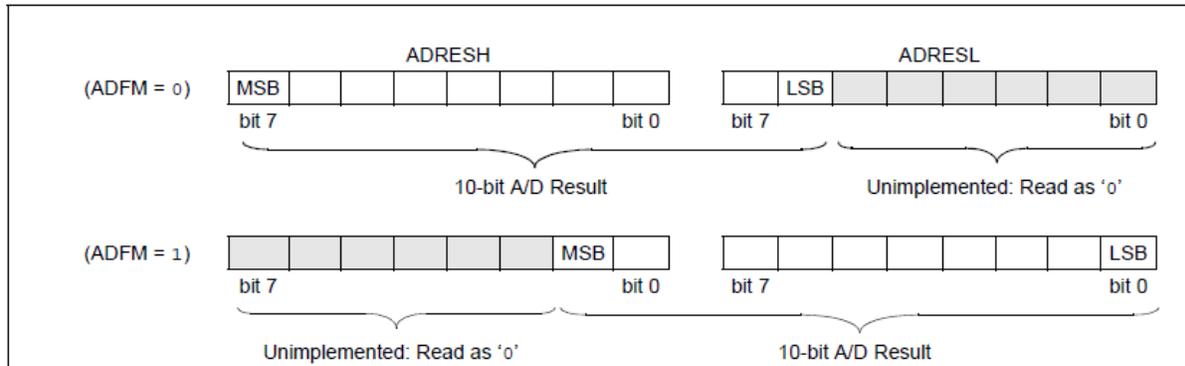


Figure 13: 10-bit A/D result format - left justified (top), right justified (bottom)

The A/D conversion takes at least  $8\mu s$  and the results are placed into two 8 bit registers depending on how the 10 bit A/D module is configured. In the right justified format the most significant bit (MSB) and 9th bit stored in the ADRESH register and the 8th bit to the least significant bit (LSB) in the ADRESL register.

Left justified made it possible to use the A/D module in an '8-bit' mode by ignoring the ADRESL bits and using only the upper 8 bits along with a test voltage controlled by a potentiometer. This allowed counting up in binary which was useful during initial A/D testing as correct operation could be verified visually using LED's connected to the microcontroller outputs. The 8-bit mode was also useful in initially verifying the connection between the laptop and microcontroller via bluetooth because transmitting a single byte counting up and down was simpler to view on a serial port monitor than packeted data.

Right justified was considered as the computation would be faster in Matlab needing only ADRESH to be bit shifted left 8 times, left justified needing ADRESH to be bit shifted 2 left and ADRESL bit shifted 6 right before addition into a 10-bit number.

The sampling rate of the A/D module is currently 10Hz, samples around 100ms apart. A/D conversion and Bluetooth transmit times take about 30ms however this may cause unnecessary transmission considering the spatial distance between readings would be 1.66m on a car travelling at 60km/h. It may be desirable to increase the sampling rate if oversampling (quickly taking multiple samples and transmitting the averaged the data) needed to be done.

## 7 Bluetooth & Matlab

### 7.1 Bluetooth module

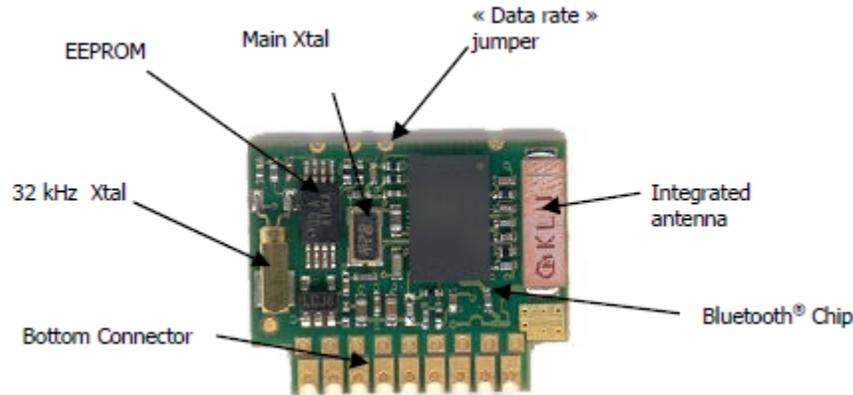


Figure 14: Adeunis ARF32 Bluetooth module

The Bluetooth module connects the sensorboard to other Bluetooth equipped platforms, in my case a laptop and in the future a smartphone. While there are several options of Bluetooth module the majority of the Bluetooth modules have similar specifications and similar prices, the lower cost modules are surface mount chips that would need soldering onto a breakout board or be permanently soldered onto a PCB. The Bluetooth module being used for this thesis the Adeunis ARF32 re-used from the 2010 Haze Watch group's sensorboard[5], chosen because it could be mounted without soldering to both a breadboard (using wires) or on a PCB (using terminal pin headers). The ARF32 runs on a supply voltage of 2.85 to 3.6v, has a UART speed of 9600 baud, can send up to 723kbps using Bluetooth 2.0 standard and is simple to interface with the PIC16F690.

Examining the supply voltage it can be seen that the device is intended to be powered from a standard 3.3v voltage rail. The ARF32 supply voltage is important in that it is the only fixed voltage rail that's needed, the gas sensor circuit and microcontroller being able to operate over a wide range of supply voltages. Because of this constraint it would be desirable to have the whole circuit running on the 3.3v rail in order to simplify the design, however as stated in the formulas sheet for better immunity to power supply ripple it would be better to split rails into 5v and 3.3v.

Considering the that I plan to send 10 packets per second, and that packet size will be 6 bytes, the bitrate needed is only 480bps, the maximum bitrate of 723kbps in this case is unnecessarily high. Any future work on the sensorboard that may change bluetooth modules will need to consider that transmission rate is of low priority. The PIC16F690 is able to use the ARF32 and transmit data serially over the ARF32 very easily. After initialisation all the PIC16F690 needs to do is write to its TXREG register and wait 5ms for the transmit to finish. Connection to a computer is also relatively simple.

## 7.2 Message structure

The Bluetooth message structure evolved from repeatedly sending a single byte of data to needing to send a packet of at least two bytes because of the 10-bit resolution of the A/D module. The message structure being used for the sensorboard is as below.



Figure 15: Message structure between sensorboard and laptop

- Flag - The flag is a simple two byte sequence for receivers to use as a starting point for reading the packet.
- Microcontroller code version - Allows for backwards compatibility if the sensorboard & message structure is updated, e.g. 2 sensors on one board.
- Device ID - The device ID will be unique to each sensorboard and programmed onto the microcontroller. When the full project is implemented a database will store which sensors are used on a specific device, each sensor having it's own calibration values of sensitivity and offset.
- Sensor Data - The sensor data is the raw voltage quantised from the gas sensor circuit rather than the actual PPM value of the gas sensor. This is because storing the calibration values server side means the microcontroller does not need to be reprogrammed every time the sensor needs recalibration.

### 7.3 Matlab

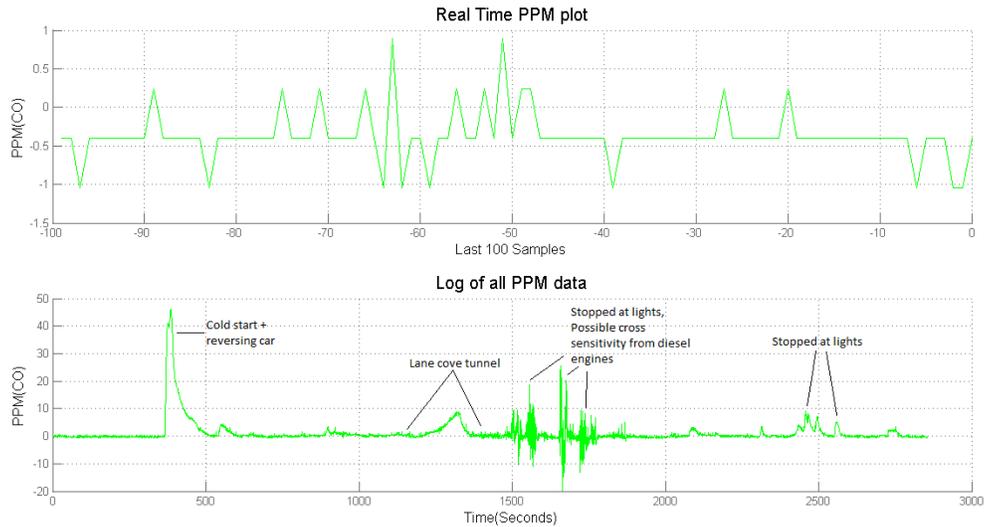


Figure 16: Raw data matlab plot

Matlab is used to get the data from the COM port and extract the pollution data from it in order to use it for testing. I've programmed it to use two subplots:

- Real time PPM plot - A rolling display of the last 100 samples is shown. This display is useful for short separated tests (such as holding the sensorboard behind a car to test correct operation) as well as viewing immediate pollution exposure.
- Log of all PPM data - This plot keeps a log of all past data so the pollution exposure throughout an experiment or during a field test can be viewed.

The above figure is the raw data from the first field test run. As can be seen in the real time plot, quantisation errors and small variations in the gas concentration cause the PPM value to hover around the actual value, there is also the issue of negative data points due to short intense changes in gas concentration cause the sensor to 'rubber band' into negative values as it tries to meet the match the actual gas concentration. This highlights the need for data conditioning by applying a filter to smooth the data and by zeroing values less than zero. This will need to be a consideration for the smartphone design which may not have access to data conditioning on par with matlab.

Having the Matlab program aided in the calibration and testing of the sensorboard. The program facilitated calibration efforts by automating much of the tedious work needed for manually recording values. In field testing it allowed for collection and display of data in real time, allowing notes to be taken to tie interesting results with recent occurrences.

## 8 Power supply

### 8.1 Power rail considerations

The first consideration for powering the circuit was the supply power rails. Looking at all the components the only hard constraint on supply voltage came from the bluetooth module, needing 3.3v. The gas sensor circuit doesn't have a set limit as it goes from a virtual ground determined by half the supply, the microcontroller can also be powered at a range of voltages. Both gas sensor circuit and microcontroller could technically use the 3.3v voltage rails (and this was the case during initial breadboard implementation) however because the gas sensor circuit must be quantised to a smaller range it would reduce noise immunity (ripples from the digital side & electrical noise could add a voltage offset). The microcontroller speed varies as shown below. Having would a oversampling.

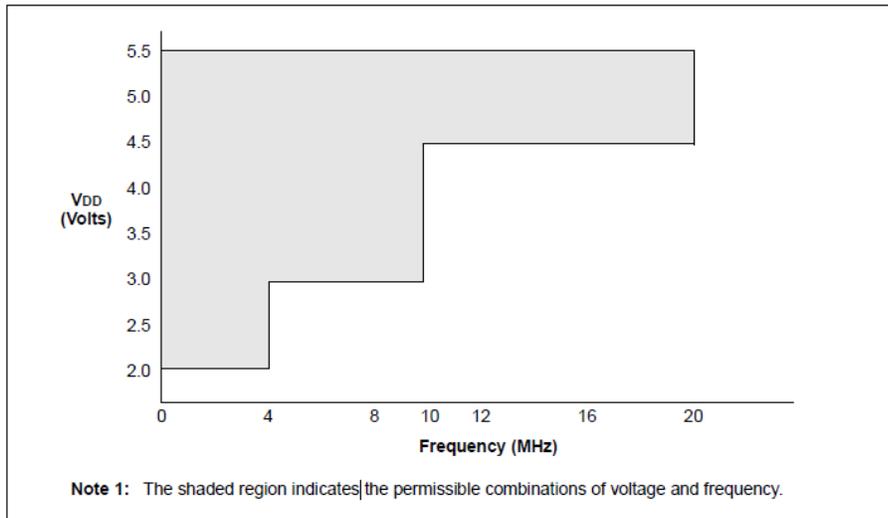


Figure 17: PIC16F690 voltage vs. operating frequency

### 8.2 Power supply rail regulation

#### 8.2.1 Linear Regulator

A linear regulator is able to maintain a steady voltage provided the battery voltage is above it's target voltage. The downside to having a linear regulator is that it uses battery inefficiently, whether 5v or 9v is put at the input, the current draw will remain the same despite the higher voltage, the extra voltage being dissipated as heat so ideally the battery voltage should be as close as possible to the target voltage. As soon as the battery voltage is less than the target voltage the device ceases to output the target voltage, as such battery life estimations need to be cut short as voltage drops with battery use.

#### 8.2.2 Boost Converter

A boost converter is able to boost the voltage from a battery to a set level at the expense of increased current drained from the battery, allowing the use of lower voltage in order to get the desired voltage on the supply rails. Boost converters also don't depend on how much voltage is left and can use almost all the power inside a battery. The disadvantage with using a boost converter is that because of how they operate they can cause ripples of up to 200mV[23] on the power rails. Considering the gas sensor has an average sensitivity of 70nA/ppm, the output from the transimpedance amplifier converts this to 14mV/ppm. This could mean an inaccuracy of 7ppm in the reading we're getting.

### 8.2.3 Choice

- Linear regulators have poor power efficiency but excellent ripple rejection properties (low disturbance on the power supply and ground rails).
- Low dropout linear regulators (LDO's) can work close to the target voltage before inoperation and negate poor power efficiency when the battery voltage is close to the target voltage.
- SMPS have great power efficiency and thus longer battery life however they can cause ripple of up to 100mV.

Considering that accuracy is the goal of this design of sensorboard I've chosen to go with using a linear regulator.

### 8.2.4 Lowering power supply ripple

In order to lower power supply ripple 100nF decoupling capacitors were adjacent to the microcontroller and bluetooth modules, the analogue (gas sensor circuit) and digital (microcontroller and Bluetooth) parts of the sensorboard were connected in a star configuration which helps though physical separation, the analogue and digital sections only meeting near the 5v linear regulator output.

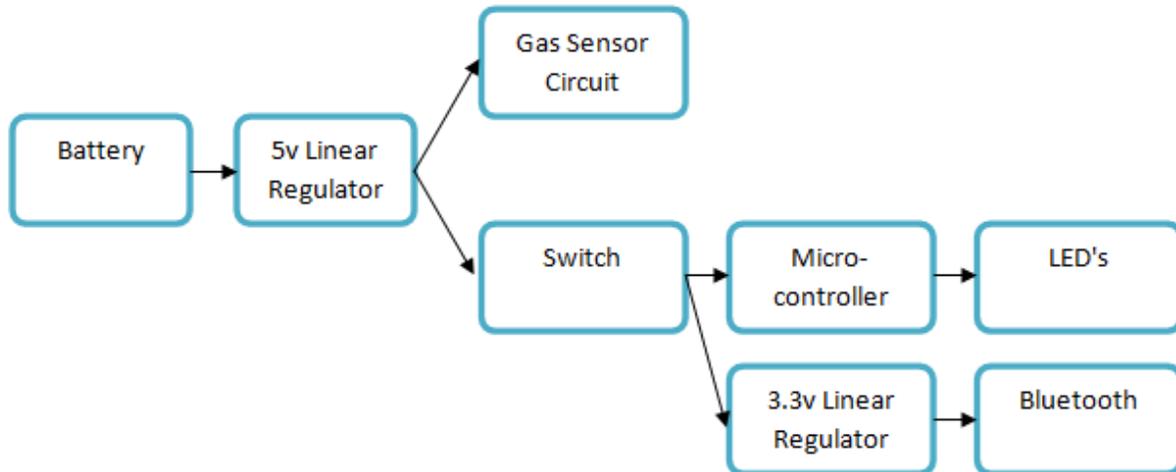


Figure 18: Power diagram of wireless sensorboard

### 8.3 Power consumption

In order to work out the capacity of battery needed the power consumption of the circuit had to be estimated. This was done by examining power use of all components. Because of the choice of using linear regulators current requirements are the main interest here, voltage becomes important as eventually the battery voltage will drop below the 5v required by the linear regulator.

Component	Description	Supply voltage	Operating current(max)
EC4-500-CO	CO Sensor	-	42.5uA
OPA2277P	Opamp	5v	525uA
OPA2277PA	Opamp	5v	525uA
LP2951ACNG	5v Voltage reg.	5v+	75uA
LP2951ACN-3v3	3.3v Voltage reg.	3.3v+	75uA
Red LED	LED	1.85v	20mA
Green LED	LED	2.1v	20mA
PIC16F690	Microcontroller	5v	1mA
ARF32	Bluetooth module	3.3v	40mA

Total maximum output current = 82.2425mA

Table 6: Sensorboard component power specifications

The above table assumes worst case scenarios for the CO sensor of 85nA/ppm at the output, 500ppm. The opamps and voltage regulators assume quiescent current only. CO voltage is left blank as it is not connected to the power supply directly, instead going through its support circuitry. The red LED is intended for showing if the pollution level is above a programmed level (hazard warning) and thus depends on how the device is used.

## 8.4 Battery choice

Because linear regulators dissipate power equal to the current draw of the rest of the circuit multiplied by the dropout voltage ( $V_{\text{battery}} - V_{\text{set}}$ ) having the total battery voltage above 5v needs to be considered. This is because the linear regulators will not function correctly if the output. In order to roughly estimate the capacity of the different battery types I've gone through the datasheets of Energizer batteries and drawn a line from when the voltage goes below 5 during constant current operation and scaling that for maximum current draw (82mA) in order to find the minimum service time. For AA & AAA batteries the  $V_{\text{cc}}$  cutoff is 1.25v considering four batteries in use.

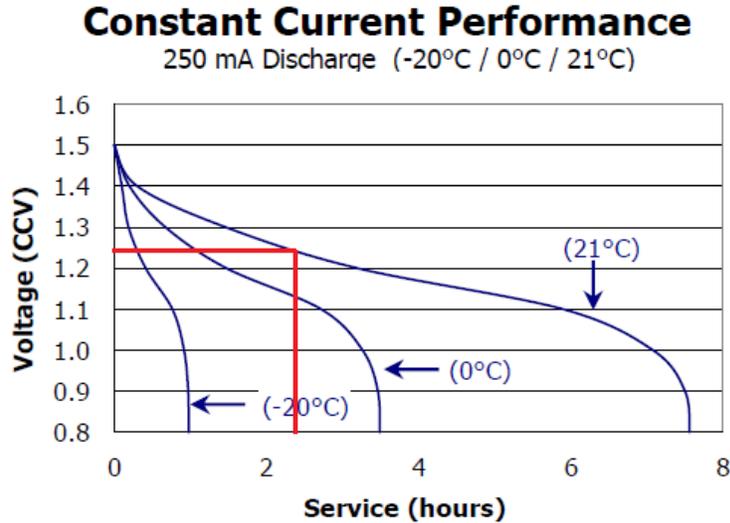


Figure 19: Battery service time estimation example for AA

Table 7 below shows the considerations for the battery types with the estimated service time as well as dimensions so the batteries can fit within the final package.

Battery Type	Nominal voltage	Estimated service time	Batteries used	Dimensions(mm)
9v - Alkaline	9v	2.5 hours	1	48.5 x 26.5 x 17.5
9v - NiMH	7.2v	1.5 hours	1	48.5 x 26.5 x 17.5
AA - Alkaline	1.5v	7.6 hours	4	50.5 x 58 x 14.5
AA - NiMH	1.25v	12 hours	4	50.5 x 58 x 14.5
AAA - Alkaline	1.5v	2.3 hours	4	44.5 x 40.2 x 10.5
AAA - NiMH	1.25v	5.5 hours	4	44.5 x 40.2 x 10.5

Table 7: Comparison of different Energizer battery types

Because of size constraints with mounting the PCB in the case I chose to use AAA batteries as their height (10.5mm) allowed the battery pack to fit within a reasonable sized enclosure. The above times were conservative considering that the times were estimated at maximum output current, in normal operation the red LED which drains 20mA when on is almost never on as it's a warning light & the Bluetooth module does not constantly transmit. In testing I've found the times to be much longer, the AAA Alkaline lasting at least 5 hours.

## 9 PCB design

In order to make the sensorboard more compact than a breadboard, and in a form that could be mounted to a car I had to design a PCB. I'm using EagleCAD for designing the PCB as it offers a large component library and has several IC manufacturers that publish parts files to add into customised libraries. For custom components such as the e2v gas sensors which had no relevant CAD file I was able to follow a guide[13] to create custom schematic parts with the relevant dimensions, labeling and drill hole & solder pad placements. When designing the PCB the textbook 'The Circuit Designer's Companion'[23] and online guides hosted on Sparkfun[18] and Instructables[22] were important in designing the PCB.

### 9.1 PCB design considerations

**Board dimensions and layers** The freeware license of EagleCAD allow a maximum of 10cm x 10cm for PCB size and 2 layers for the PCB. Having increased layers makes routing tracks easier and neater but comes at an increased cost when manufacturing the PCB.

**Surface mount technology (SMT) vs Through Hole** These two technologies describe the style that components are placed on the PCB. SMT is generally superior as the component dimensions are smaller and costs are lower allowing smaller cheaper boards to be produced. I have chosen to go with through hole as components are easier to solder onto the board, the components are proven to work and errors in production could be corrected through track cutting and air-wire soldering.

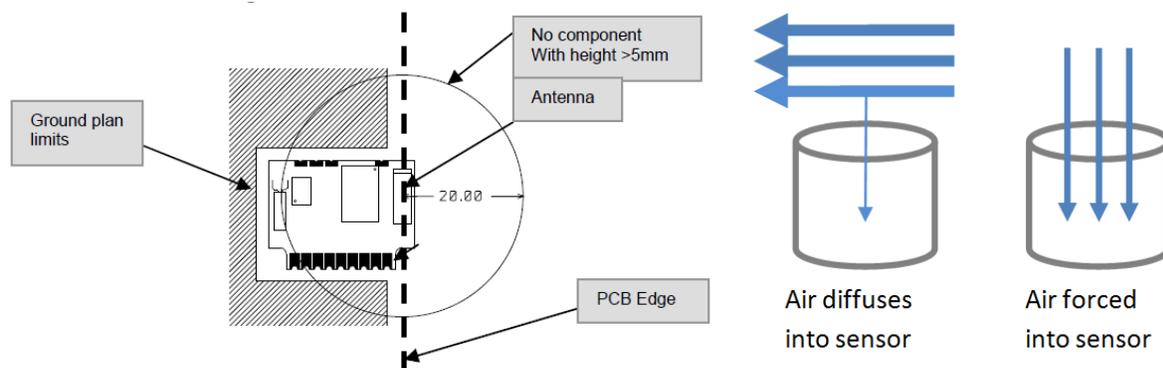


Figure 20: Bluetooth and gas sensor placement considerations

**Component placement** Component placement was important for the bluetooth module and for the analogue and digital components on the board. The Bluetooth module datasheet needed the antenna clear of other components taller than 5mm and ideally at the edge of the PCB. Examining the gas sensor, our accurate results were taken in lab conditions however in actual use on a car air could be hitting the sensor at up to 70km/h. In order to ensure that our results aren't skewed by this it's preferable to have gas diffuse from the side rather than be forced into the sensor. As such the sensor should be mounted into the PCB such that it isn't facing the direction of travel.

**Additional features** Differing from the breadboard implementation, extra features were added to help user friendliness. Two LED's were added, a green LED being an 'on' indicator and a red LED intended as hazard warning light for when the concentration of pollutants detected exceeds a set level. Both LED's are controlled by the microcontroller so can be reprogrammed if need be.

DIP mounting sockets are used for two main reasons. The first is that the microcontroller is programmed separately before being put into the sensorboard, if the software needs to be updated for the microcontroller

then there needs to be a way to unplug and plug back the microcontroller. The second reason for DIP mounting sockets is re-use of the IC components. With the expensive \$15 OPA2277P OPAMPs it made sense to make them re-useable between board designs. With the total component cost of DIP IC's at \$23.12 it would allow for a reasonable cost saving between board re-designs.

## 9.2 Design guidelines

The following sources were useful in designing the PCB. As well as giving steps on how to proceed there were general outlines as to what should be expected on the final board.

### 9.2.1 The Circuit Designer's Companion

- Avoid 90 degree and acute angles in track placement as it results in trapped etchant which could corrode tracks.
- For good decoupling of the power rails against low frequency ripple there needs to be at least a 1uF tantalum capacitor per 2-3 medium/large scale integrated chips such as our microcontroller.
- For each package add a 10-100nF capacitor for decoupling, such as the Bluetooth module and microcontroller.
- Segregate analogue and digital supply and ground rails, connecting them at only one point (star connected)

### 9.2.2 Turn your EAGLE schematic into a PCB (Instructables)

- Arrange components in the board design before routing
- Ensure to load design rules that conform with the PCB manufacturers specifications
- Check board against design rules while designing to ensure no errors (e.g. trace width, drill hole spacing)
- Smash packages (separate part number/text from physical outline) and position so that text from adjacent parts doesnt overlap

### 9.2.3 Better PCBs in Eagle (Sparkfun)

- Ground planes need reasonable distance from other tracks.
- Label all components to make it easier to assemble and position. Also lowers chance of incorrect component placement.

### 9.3 Enclosure & mounting

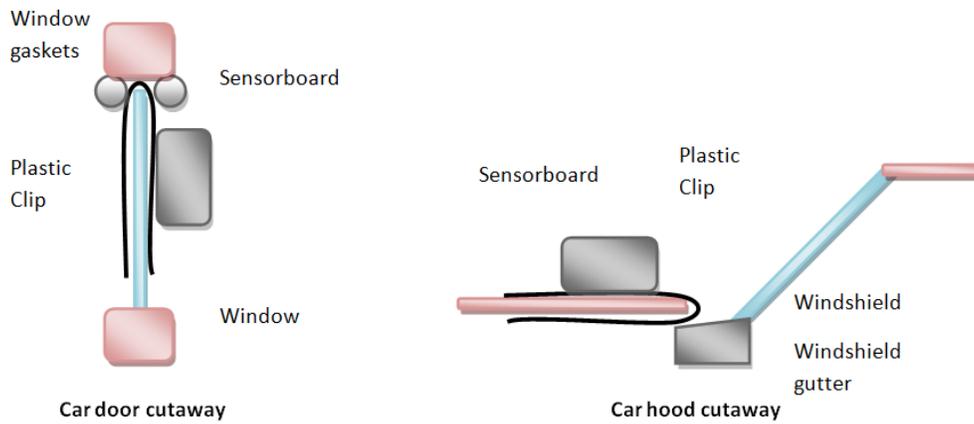
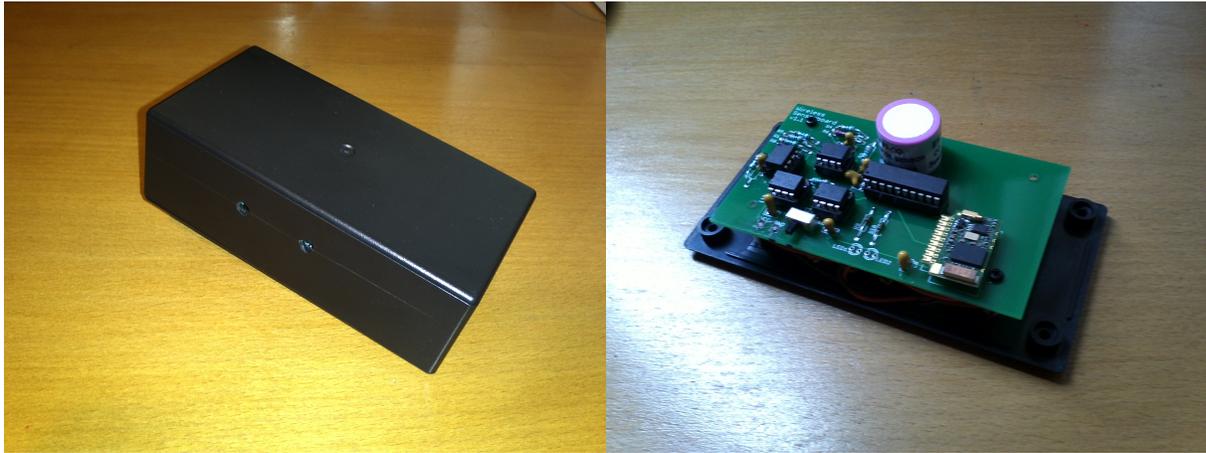


Figure 21: Jiffy Box enclosure & Mounting ideas

An enclosure to house the PCB was incorporated into the design of the PCB through standoff screw holes. The enclosure was necessary to protect the components during use as well as in limiting airflow so air isn't forced into the sensor.

The PCB was designed around using a 130x67x44mm Jiffy Box enclosure, the smallest size of enclosure that would fit the PCB. The minimum height needed was dictated by the sensors. Considering the sensor height of 20.9mm and that AAA battery height is 10.5mm at least 30.1mm clearance was needed, not including the heights of the sensor sockets & battery enclosure. The length and width of the jiffy box was enough to contain the finished PCB.

There were several ideas for mounting the case including mounting onto the car door window by jamming a plastic clip into the rubber gasket and mounting into the gap between the windshield gutter and the bonnet. These ideas weren't able to be realised as no off the shelf clip could be found to strongly secure the Jiffy box.

## 9.4 Wireless sensorboard v1.0

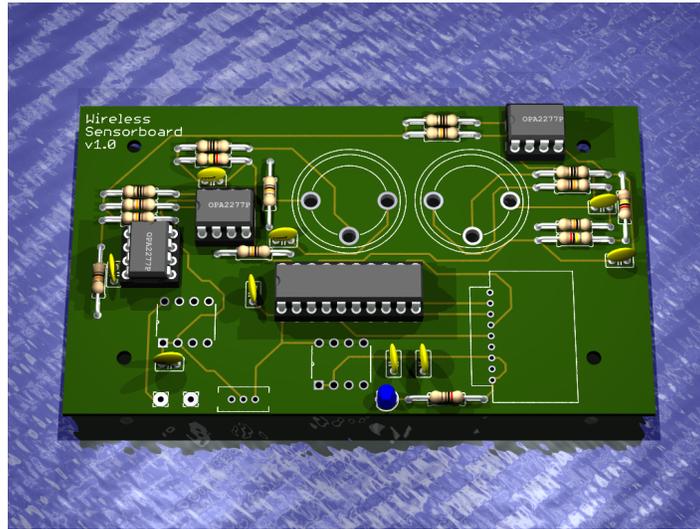


Figure 22: Wireless sensorboard 1.0 (Eagle3D render)[21]

### 9.4.1 Introduction

The first design of the wireless sensorboard featured two sensors, the CO sensor and the NO<sub>2</sub> sensor. This was the first model of the wireless sensorboard, the PCB manufactured by PCBCart at a cost of about \$15 per board including shipping.

### 9.4.2 Issues

- Errors during component placement in EagleCAD. OPAMPs had input terminals inverted and needed track cutting and air-wire resoldering to fix.
- Conversion from schematic to board ignored some tracks, i.e. tracks appeared on schematic view but were absent in the PCB needing air-wire connections to fix.
- Mounting holes for the ARF32 bluetooth module was too small for terminal pins. With no dimensions listed on the ARF32 datasheet for connection holes a value for the terminal holes was chosen on the PCB design which was incorrect.
- Possible cross-interference between microcontroller A/D pins. With CO sensor plugged in and NO<sub>2</sub> sensor absent, NO<sub>2</sub> pin was had some correlation with CO sensor result. Could be a faulty connection or could be issue with microcontroller.

### 9.4.3 Summary

This design was flawed as a program error from schematic design to board design had left out some tracks, needing extensive cutting & resoldering of tracks, the board taking about 6 hours to solder in airwires. Despite the fix the board did not perform correctly and would be unfeasible to solder multiple units. With the mounting holes for the ARF32 too small it required air wire connections which couldn't be secured. Finally with the possibility of cross interference of the two A/D pins the design reverted to using only one sensor as calibrations testing had been done with a single sensor before.

**Bill of Materials for Wireless Sensorboard v1.0 (As of 12.6.12)**

<b>Component</b>	<b>Description</b>	<b>Units</b>	<b>Cost</b>	<b>Subtotal</b>	<b>Total</b>
LP2951ACNG	5V Lin reg	1	\$1.43	\$1.43	\$282.00
LP2951ACN-3.3G	3V Lin reg	1	\$1.43	\$1.43	
OPA2277P	Dual precision OPAMP	2	\$15.60	\$31.20	
OPA2277PA	dual OPAMP for 5v	1	\$4.66	\$4.66	
ARF32	Bluetooth Module	1	\$62.11	\$62.11	
LED	Blue LED	1	\$1.01	\$1.01	
EC4-500-CO	CO Sensor	1	\$45.76	\$45.76	
EC4-20-NO2	NO2 Sensor	1	\$95.16	\$95.16	
10 Ohm	Resistor	4	\$0.09	\$0.34	
200 Ohm	Resistor	1	\$0.10	\$0.10	
10k Ohm	Resistor	8	\$0.08	\$0.64	
200k Ohm	Resistor	3	\$0.10	\$0.30	
1uF	Capacitor(Tantalum)	2	\$0.32	\$0.63	
100nF	Capacitor(Tantalum)	7	\$0.22	\$1.51	
SPC15501	IC 20 pin socket	1	\$0.42	\$0.42	
DILB8P-223TLF	IC 8 pin socket	5	\$0.09	\$0.43	
450-3326-01-03-00	Cambion sockets (sensors)	6	\$1.76	\$10.56	
OS102011MA1QN1	Slide switch	1	\$1.32	\$1.32	
Jiffy 130x67x44mm	Jaycar Jiffy box	1	\$3.95	\$3.95	
	Battery holster	1	\$1.65	\$1.65	
	Screws	4	\$0.12	\$0.48	
	Standoffs	4	\$0.48	\$1.91	
	PCB	1	\$15.00	\$15.00	

## 9.5 Wireless sensorboard v1.1



Figure 23: Wireless sensorboard v1.1

### 9.5.1 Introduction

The second sensorboard was able to successfully incorporate changes learned from the mistakes of the first sensorboard manufacturing, reverting back to using a single sensor worked. In addition a manufacturer, Itead PCB, was found that could manufacture PCB's at a cost of \$5 per unit. An extra LED was added for utility purposes such as a gas concentration warning light if concentration got too high.

### 9.5.2 Issues

- When the switch is off the microcontroller is able to steal some power from the analogue A/D pin. While the bluetooth turns off correctly the red LED is weakly on.
- This seems related to some connectivity issues as sometimes to connect the sensorboard to the laptop the microcontroller needs to be reset by having a battery popped out then in rather than using just the switch.

### 9.5.3 Summary

Overall the sensorboard works well and can detect and send gas concentrations over bluetooth to the laptop and shows promising results.

**Bill of materials for Wireless Sensorboard v1.1 (As of 12.6.12)**

<b>Component</b>	<b>Description</b>	<b>Units</b>	<b>Cost</b>	<b>Subtotal</b>	<b>Total</b>
LP2951ACNG	5V Lin reg	1	\$1.43	\$1.43	\$155.76
LP2951ACN-3.3G	3V Lin reg	1	\$1.43	\$1.43	
OPA2277P	Dual precision OPAMP	1	\$15.60	\$15.60	
OPA2277PA	Dual OPAMP for 2.5v	1	\$4.66	\$4.66	
ARF32	Bluetooth Module	1	\$62.11	\$62.11	
LED	Coloured LEDs	2	\$1.01	\$2.02	
EC4-500-CO	CO Sensor	1	\$45.76	\$45.76	
EC4-20-NO2	NO2 Sensor	0	\$95.16	\$0.00	
10 Ohm	Resistor	2	\$0.09	\$0.17	
2k Ohm	Resistor	1	\$0.10	\$0.10	
10k Ohm	Resistor	4	\$0.08	\$0.32	
200k Ohm	Resistor	1	\$0.10	\$0.10	
1uF	Capacitor(Tantalum)	2	\$0.32	\$0.63	
100nF	Capacitor(Tantalum)	5	\$0.22	\$1.08	
SPC15501	IC 20 pin socket	1	\$0.42	\$0.42	
DILB8P-223TLF	IC 8 pin socket	4	\$0.09	\$0.34	
450-3326-01-03-00	Cambion sockets (sensors)	3	\$1.76	\$5.28	
OS102011MA1QN1	Slide switch	1	\$1.32	\$1.32	
Jiffy 130x67x44mm	Jaycar Jiffy box	1	\$3.95	\$3.95	
	Battery holster	1	\$1.65	\$1.65	
	Screws	4	\$0.12	\$0.48	
	Standoffs	4	\$0.48	\$1.91	
	PCB	1	\$5.00	\$5.00	

## 10 Experimental procedure & results

In order to verify the accuracy of the sensorboard and even just find the calibration constants of the sensorboard experimentation needed to be performed. Through this thesis there were three main stages of testing:

1. Testing the gas sensor circuit to verify it's accuracy.
2. Testing the breadboard implementation to verify accuracy and find calibration constants.
3. Field testing.

The initial tests of the gas sensor circuit were performed by Shern Yap, at UNSW on a Taste of Research summer scholarship during the summer of 2011/2012 who designed a testing method for the gas sensor circuit and was able to calibrate some sensors. During S1 2012 testing of the breadboard implementation of the circuit was performed by Judy Liu, doing thesis B, who improved upon Shern's calibration methods, formalised the calibration equations and found the calibration constants for several CO and NO<sub>2</sub> sensors. Below I will outline their testing with relevance to the accuracy of the circuit.

### 10.1 Gas sensor circuit

#### 10.1.1 Aims

At this stage of testing the gas sensor circuit had been built, the basic equations had been derived from the circuit diagram and CO gas had been applied to the sensor to get a response. The electrochemical gas sensors had to be shown to be viable as an option to use for the sensorboard.

#### 10.1.2 Shern Yap's Gas sensor circuit testing & calibrations

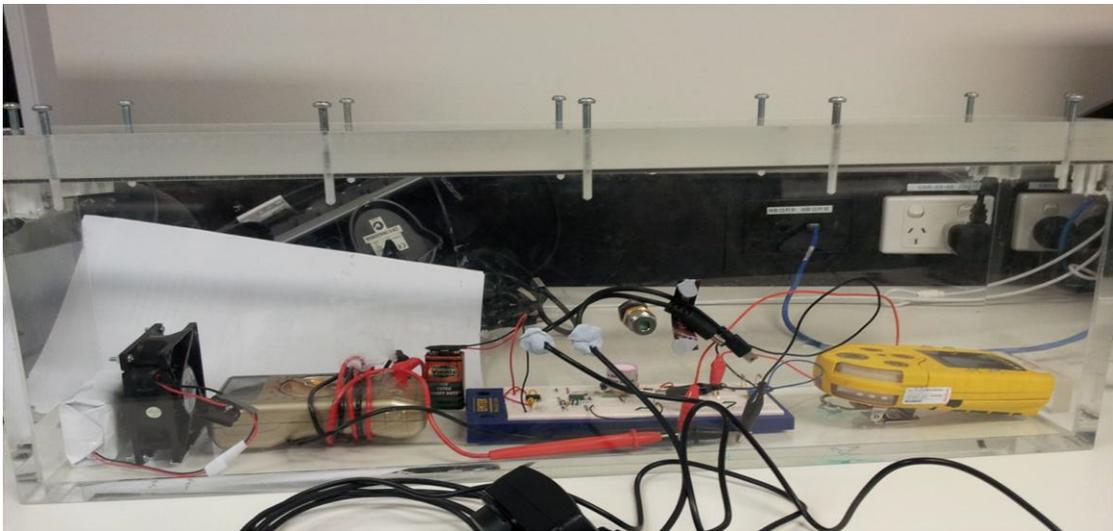


Figure 24: Shern's Testing setup[25]

The testing setup, from left to right, included a fan to mix the CO gas, a multimeter to check the voltage output of the circuit, the gas sensor circuit on a breadboard and the yellow GasAlertMicro 5 commercial gas monitor, all of this housed within a sealed perspex chamber.

The circuit was tested in the chamber as follows:

1. Fill chamber with CO from car exhaust through a septum then tighten the septum so no gas escapes.

2. Wait a set time for gas to be mixed evenly, e.g. 5-10 minutes.
3. Record values displayed on the LCD's of the multimeter (gas sensor circuit voltage) and gas monitor (ppm of CO).
4. Open septum to let some gas out.
5. Repeat steps 2 to 4 for a few hours.
6. Use ohms law  $I = V/R$  to convert the multimeter voltage to gas sensor output current.
7. Plot output current vs. ppm of CO reading to form a line.
8. Compare the sensitivity (slope of the line) against the datasheet listed sensitivity values of 55-85nA/ppm.

### 10.1.3 Results

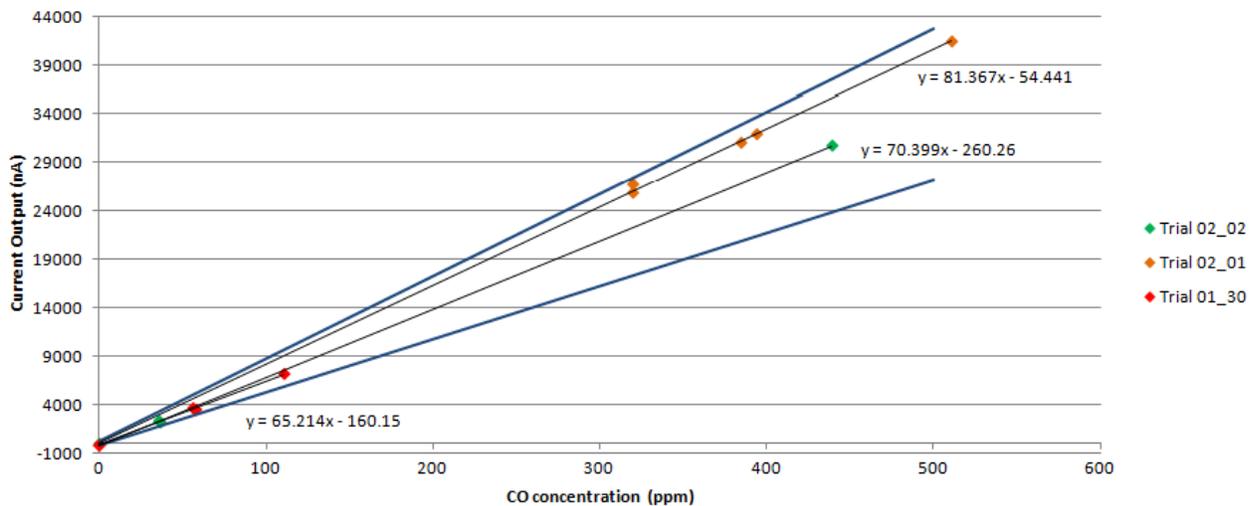


Figure 25: Testing results

From the results it can be seen that the sensitivity is completely linear and is within the datasheet values of 65 to 85 nA/ppm. Here the sensor sensitivities are 65.214, 70.399 and 81.367nA/ppm. This demonstrated that sensitivity doesn't change with CO concentration and that electrochemical sensors are ideal to use as once the calibration constants have been found.

What was also found was that the sensor needed to be powered in the biasing circuit for up to 9 hours (for destabilised sensors) for the zero-reading offset to not move, here the two sensors offset can be read from the line equations at less than 1 ppm (54nA/81nA) for the top line and less than 4 ppm (260nA/70nA) for the bottom line.

### 10.1.4 Issues

The main issue for Sherns testing was that gathering data was slow, as stated above getting information for only one sensor took several hours of active measurements, this added to the fact that readings were read from LCD screens introduced human error into the readings. In order to be able to calibrate and test effectively the testing needed to be automated which is where the full breadboard implementation comes in.

## 10.2 Breadboard Implementation

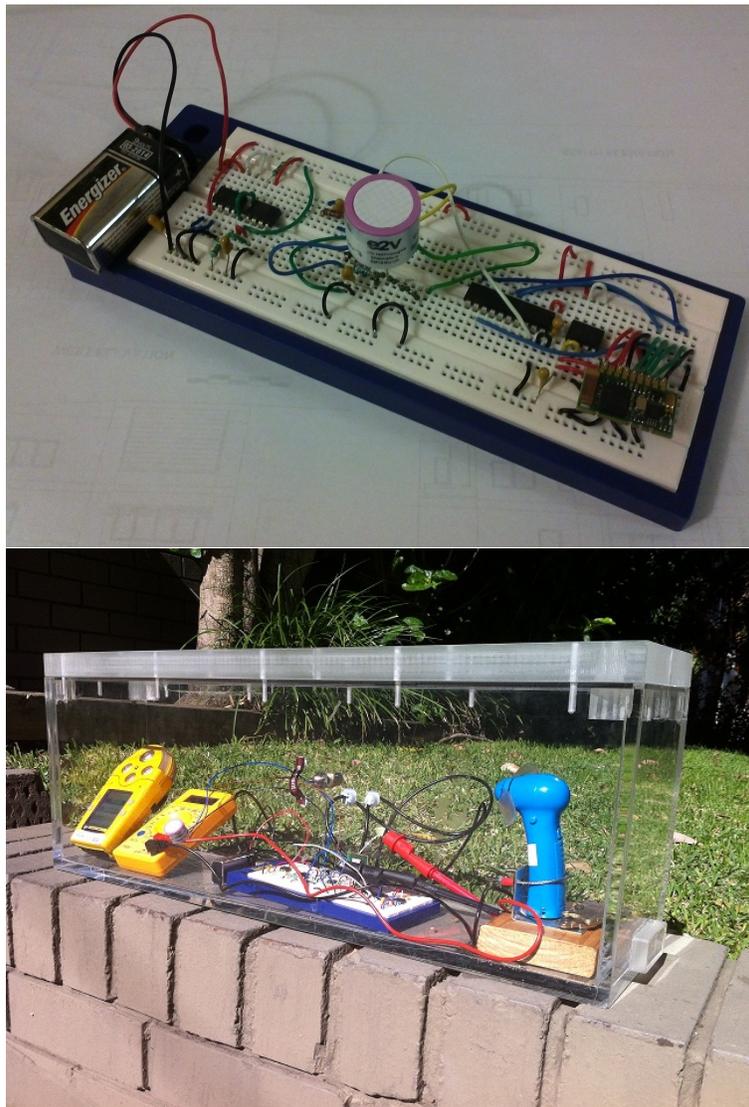


Figure 26: Breadboard implementation of sensorboard (top) & Judy's gas testing setup (bottom)

The full breadboard implementation (including the microcontroller, bluetooth module and matlab program) paired with the data logging function of the commercial meter allowed testing to become easier, automated and accurate. By leaving a small hole in the side of the tank gas could escape and results could be stored automatically without need to manually record plot points.

### 10.2.1 Judy Liu's testing & calibrations

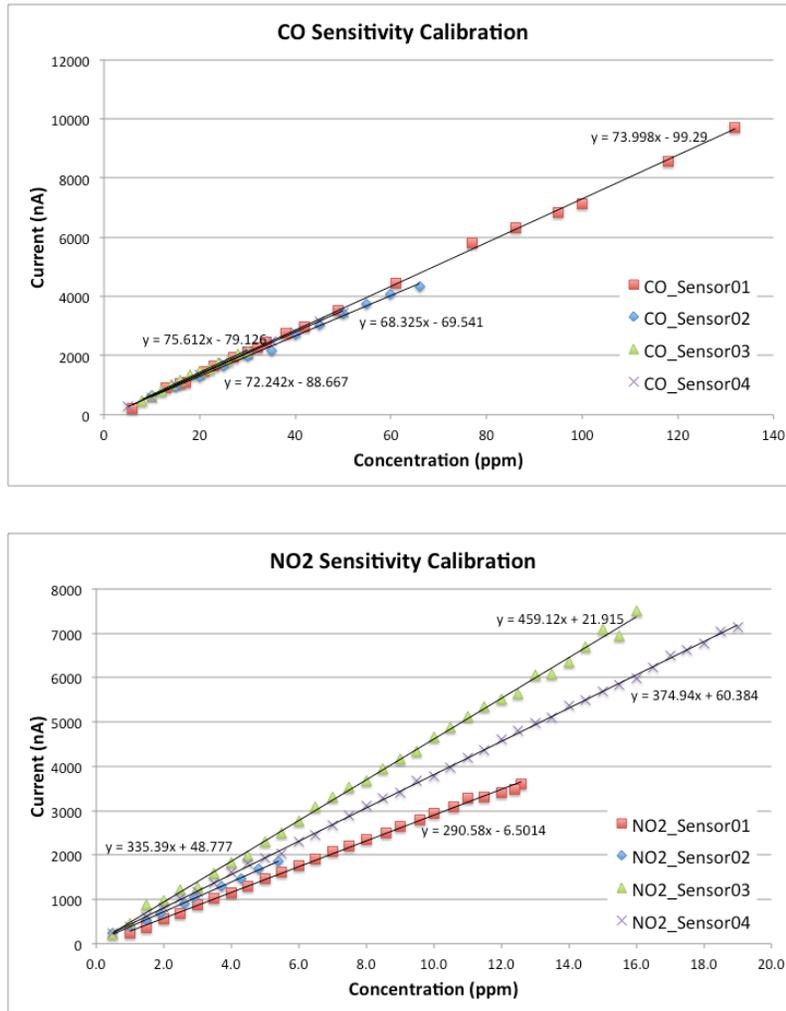


Figure 27: Calibration plots for individual CO & NO2 sensors[14]

Judy's calibration plots were similar to Shern's however Judy was able to calibrate much faster, with sensors that hadn't been destabilised it was found that stabilisation time was generally less than 30 minutes. Throughout her thesis she was able to calibrate 7 CO and 7 NO2 sensors for use with the sensorboard as well as test and compare the commercial gas monitor and the sensorboard to see how well they correlate.

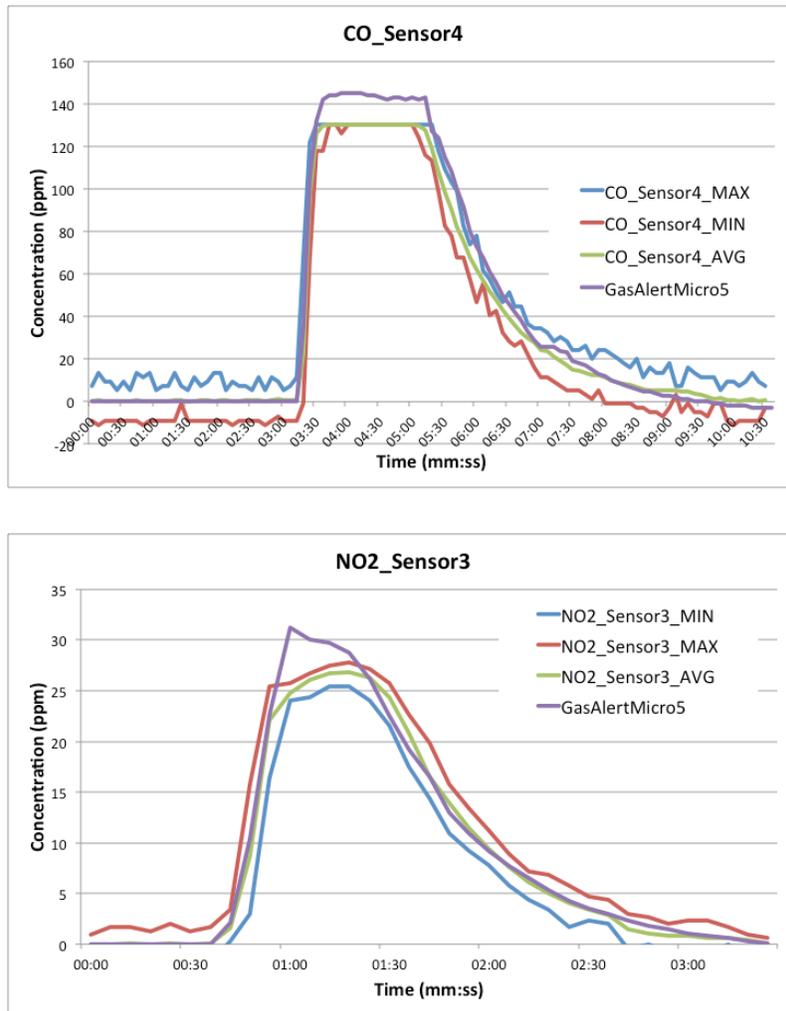


Figure 28: Test plot of CO & NO2 concentrations using sensorboard against commercial meter

The above plots were the PPM output of two specific sensors that had been calibrated then tested, gas being pumped into the tanks very quickly at the start then gradually released. The commercial gas meter is the purple line in the plot while the sensor's maximum, minimum and average are blue, red and green respectively. From the plots it can be observed that the sensorboard readings correlate well with the commercial meter and as such the sensorboard can be considered accurate. A few points of note on the plots however:

- In the CO plot our sensorboard readings stop at around 135ppm as this is what the maximum had been set to, as stated before the range of our sensorboard has been restricted in order to obtain a higher resolution at the lower concentration ranges.
- In the CO plot there is need for data conditioning as the raw data fluctates from the sensorboard. Averaging is needed in order to get an accurate result, this notion highlighted by the average CO concentration and commercial meter results (green and purple lines) which are almost identical.
- In the NO2 results it can be observed that the sensor could have problems at very high concentrations of NO2, but this should not be an issue as concentrations this high should not exist outside of lab testing and industrial gas leaks.

### 10.3 Field testing

Field testing was done to confirm if the sensorboard would be able to fulfill the goal of being car mounted while also being compared against the performance of the commercial meter. As tunnels are notorious for being filled with pollution I aimed at testing the Lane Cove tunnel as well as the M5 tunnel. In order to achieve better results I positioned both devices adjacent to each other on the front of a car and made them secure with duct tape, a precaution against losing the equipment to high speed winds when driving.



Figure 29: Mounting both devices to a car

Data was sent to a laptop running Matlab in the passengers seat, interesting occurrences on the Matlab plot were noted down and linked with an event such as being stopped behind a specific type of car, or entering/exiting a tunnel.

### 10.3.1 Field test 1 - Route through Lane Cove tunnel

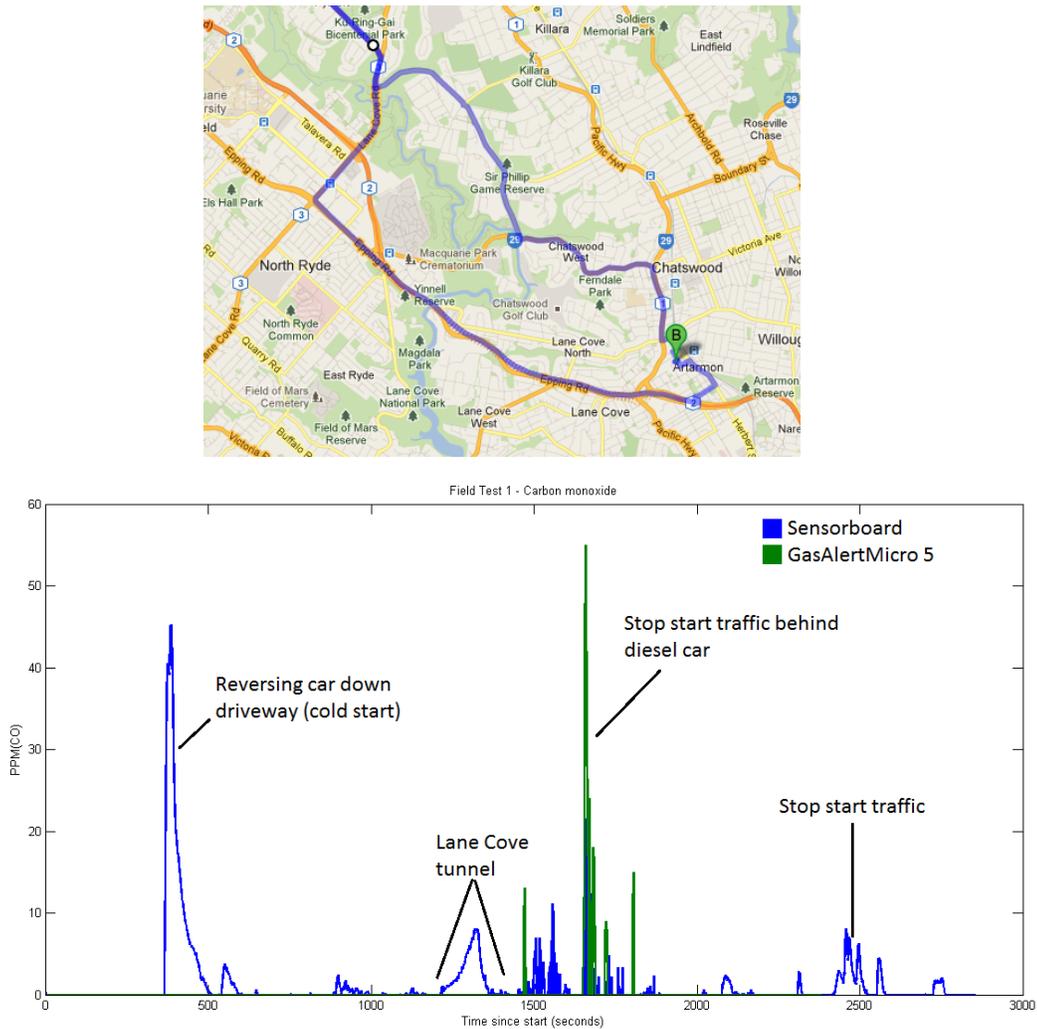


Figure 30: Field test 1 - Route and plot

The first field test took a trip through Lane Cove tunnel from an entrance near Ryde the exit at Artarmon. Going down the driveway from a cold start a high pollution is expected as a car’s catalytic converter needs to warm up before operation. Through the lane cove results were seen although still relatively low with a peak of less than 10ppm in the middle of the tunnel. Shortly after the tunnel I was in traffic for a time behind a Golf TDI diesel engine car. This was the only time the GasAlertMicro registered, as well as this the sensorboard had difficulty reacting to the bursty levels of CO given off by this section of the trip. At the end some stop start traffic registered a reasonable CO increase.

From this field test it is shown that the sensorboard works and has results within expected values although had trouble with rapid changes in concentration within a very small time frame. What was also found was that the GasAlertMicro had trouble picking up readings below 10ppm and didn’t seem to register the initial burst of CO at the start of the trip, only the pollution behind the diesel car. While this field test showed the device worked the accuracy could not be compared against the GasAlertMicro. This prompted the need for another field test, and if need be a more sensitive gas sensor.

### 10.3.2 Field test 2 - Route through M5 tunnel

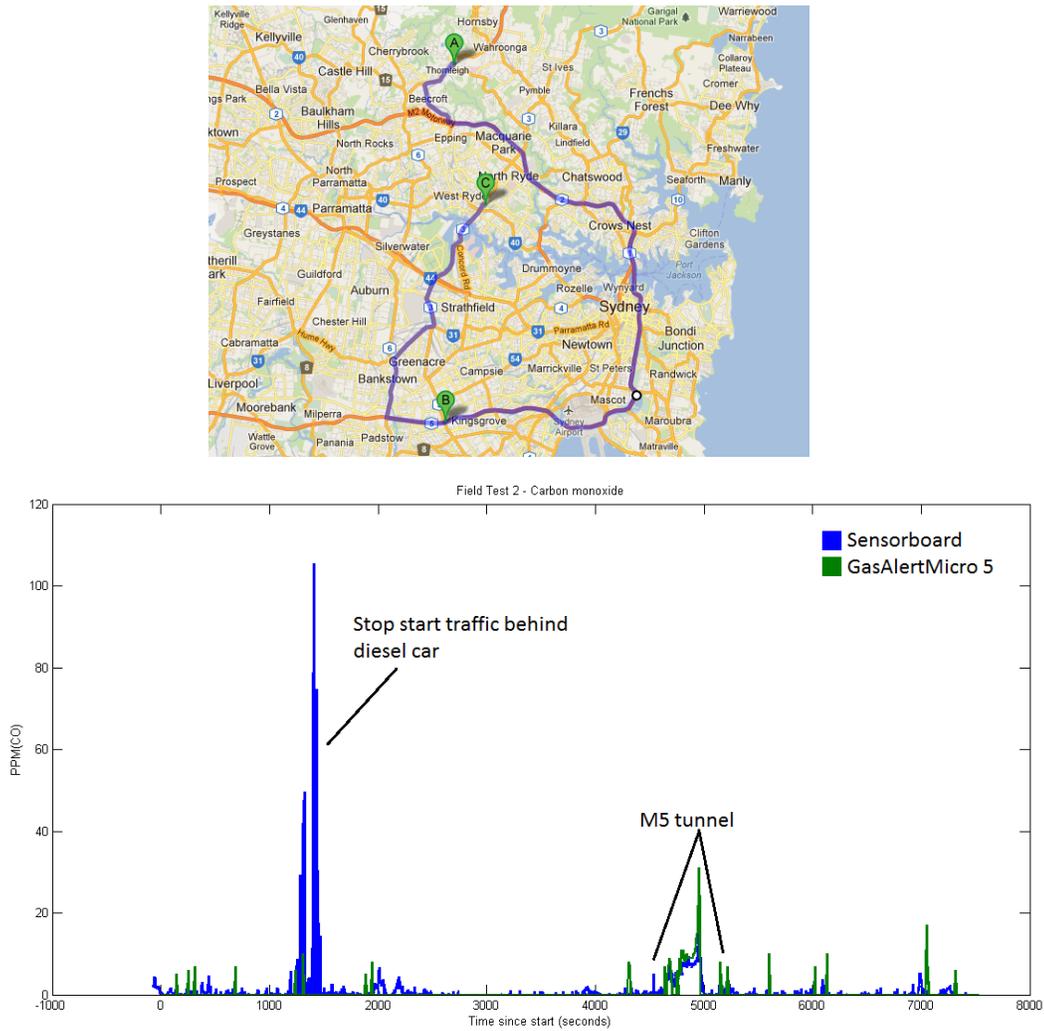


Figure 31: Field test 2 - Route and plot

The second field trip took a route from thornleigh, down to the airport with the aim of entering M5 tunnel from the east near the airport to the exit of the tunnel. There are two main points of interest here, the first being the bursty readings during start stop traffic behind a Rodeo 3.2L V6 diesel vehicle. The second point of interest was the M5 tunnel.

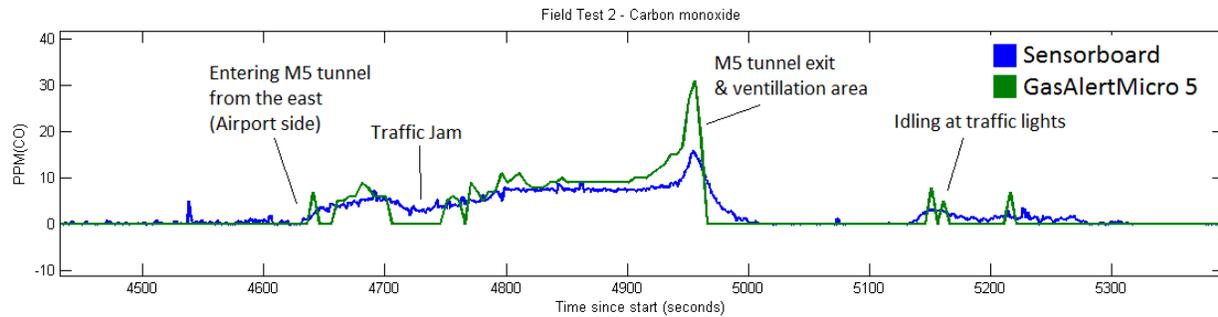


Figure 32: M5 tunnel from east to west

Examining the M5 tunnel more closely it can be seen that the results of the sensorboard and GasAlert-Micro correlate very closely and is within expected values. During the tunnel a traffic jam where car's are idling means less emissions being given off, and the large ventilation shaft which draws most of the pollution out at the west side of the tunnel has an expectedly higher gas concentration. The thing of note in terms of device results is that the GasAlertMicro reacts faster to gas concentrations whereas the sensorboard is slower to gain and lose gas concentrations even though in the middle of the tunnel where the concentration is steady they are the same. This can be explained by the mounting of the board. As the GasAlertMicro has the sensor exposed and is slightly facing the wind it can react faster but may read in a higher value than the actual concentration. Because the airflow in the sensorboard is impeded by the enclosure gas has more trouble entering and leaving the enclosure. Also as the sensor is faced perpendicular to the direction of travel, gas is diffused into the sensor more than it is forced.

## 11 Future work

### 11.1 Hardware improvements

- The method for securing the Jiffy Box to the car still needs method to be found such that the it wont detach at high speed.
- Surface mount components could be used to shirnk the board size drastically and reduce manufacturing costs. Having a lighter smaller unit would also help in mounting.
- Have a socket on gain resistor pins so one board can configured for both NO2 and CO rather than one or the other
- Use an independant A/D module with higher resolution for improved accuracy
- Look into cheaper/smaller bluetooth modules to improve battery life

### 11.2 Software Improvements

- Sleep modes on microcontroller and bluetooth modules to save power
- Have two way communication so settings on the microcontroller can be adjusted from Matlab/ a smartphone such as period between transmissiosn

### 11.3 Integration into Haze Watch

- Integrate the sensor board with the upcoming updated Haze Watch systems, primarily the interface with the Android smartphone.

## 12 Conclusion

The sensorboard design has been a success, data can be transmitted to the laptop and the results correlate well with the commercial gas monitor. Focusing on the sensorboard's accuracy; Shern's testing confirmed that the electrochemical sensors were linear and were the right direction to go when choosing gas sensor technology, Judy's testing proved in lab conditions and with data conditioning (averaging) the sensorboard results are almost identical to the commercial gas meter. From the field testing it seems that air-flow does seem to play a part in the gas readings, especially at high speed and that mitigating the effects of airflow into the sensor by using an enclosure will allow for a more ideal condition to measure pollution.

There are several health risks due to air pollution and a desire to monitor air pollution at a higher resolution because of this. The sensorboard results correlate well with the commercial gas monitor and the gas sensor is ready to be integrated into the other Haze Watch systems including connection to a smartphone. With the full system implemented it will make high resolution air pollution mapping possible, allowing people to manage their exposure to air pollution and putting us a step forward in controlling air pollution.

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## 13 Appendix

Name	Pages	Description
EC4-500-CO	1	Datasheet for the e2v carbon monoxide sensor
EC4-20-NO2	1	Datasheet for the e2v nitrogen dioxide sensor
MK_Sensorboard_Sch	1	Schematic design of sensorboard unit
MK_Sensorboard_Brd	1	PCB design of sensorboard unit
Calibration Results	1	Calibration results summary from Judy Liu
MK_Sensorboard_Code	2	Microcontroller code
MK_Matlab	3	Matlab program code (For a CO sensor)

### PERFORMANCE

Range ..... 0 - 500 ppm  
 Maximum overload..... 1500 ppm CO  
 Sensitivity..... 55 - 85 nA/ppm CO  
 Zero in air at 20 °C..... <±3.1 ppm CO  
 Resolution..... 1 ppm CO  
 Linearity ..... linear across range  
 Response time, t90..... <30 s  
 Long-term output drift..... <2% signal/month  
 Warranty ..... 2 years

### OPERATING CONDITIONS

Temperature range ..... -20 to +50 °C  
 Operating humidity..... 15 - 90% RH (non-condensing)  
 Pressure range ..... 90 - 110 kPa (nominal)  
 Operating circuit..... see Electrochemical Toxic Sensor Application Note  
 Applied potential ..... 0 V  
 Storage life..... 6 months in original packaging (0 - 25 °C)

### PHYSICAL CHARACTERISTICS

Label colour ..... silver  
 Weight..... 5 g approx.  
 Dimensions ..... see outline

This device is designed to be RoHS compliant.

### CROSS-SENSITIVITY DATA

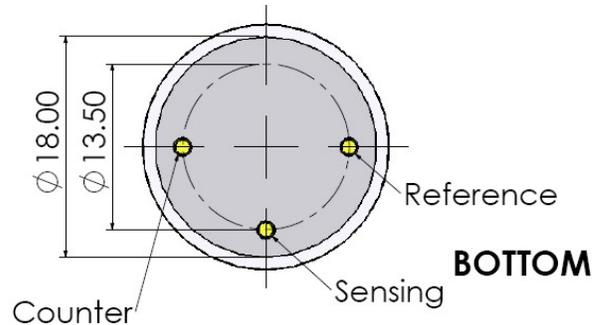
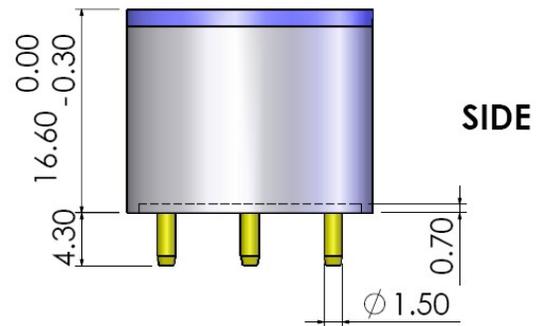
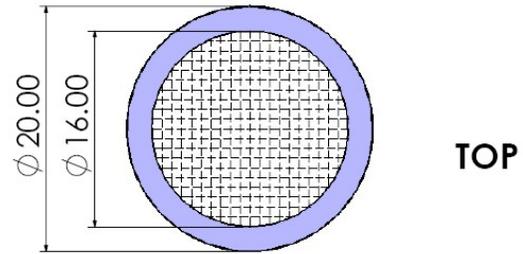
GAS	Concentration (ppm)	Sensor Response (As ppm CO)
Hydrogen Sulfide	24	0
Sulfur Dioxide	5	0
Chlorine	10	0 to 1
Nitric Oxide	25	0
Nitrogen Dioxide	5	0
Hydrogen	100	<40
Ethene	100	<16

### Important Note

Do not solder to the connector pins as this may damage the sensor and thereby invalidate the warranty.

Details on recommended connector pins can be found in the Frequently Asked Questions within the Gas Sensor section of the e2v website.

### OUTLINE



All dimensions in mm.  
 All tolerances ±0.15mm unless otherwise stated.

Whilst e2v technologies has taken care to ensure the accuracy of the information contained herein it accepts no responsibility for the consequences of any use thereof and also reserves the right to change the specification of goods without notice. e2v technologies accepts no liability beyond the set out in its standard conditions of sale in respect of infringement of third party patents arising from the use of tubes or other devices in accordance with information contained herein.

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e2v technologies inc. 520 White Plains Road, Suite 450, Tarrytown, NY10591 USA Telephone: (914) 592-6050 Facsimile: (914) 592-5148 e-mail: [enquiries@e2vtechnologies.us](mailto:enquiries@e2vtechnologies.us)

### PERFORMANCE

Range ..... 0 - 20 ppm  
 Maximum overload..... 250 ppm  
 Sensitivity (see note)..... 450 - 750 nA/ppm NO2  
 Zero in air at 20 °C..... <0.9 ppm NO2  
 Resolution..... 0.1 ppm NO2  
 Linearity .....linear across range  
 Response time, t90..... <35 s  
 Long-term output drift..... <2% signal/month  
 Warranty ..... 2 years

**Note:** This output current is negative. This is because the sensor reaction is a reduction of the target gas.

### OPERATING CONDITIONS

Temperature range ..... -20 to +50 °C  
 Operating humidity..... 15 - 90% RH (non-condensing)  
 Pressure range ..... 90 - 110 kPa (nominal)  
 Operating circuit..... see Electrochemical Toxic Sensor Application Note  
 Applied potential ..... 0 V  
 Storage life..... 6 months in original packaging (0 - 25 °C)

### PHYSICAL CHARACTERISTICS

Label colour ..... silver  
 Weight..... 5 g approx.  
 Dimensions ..... see outline

This device is designed to be RoHS compliant.

### CROSS-SENSITIVITY DATA

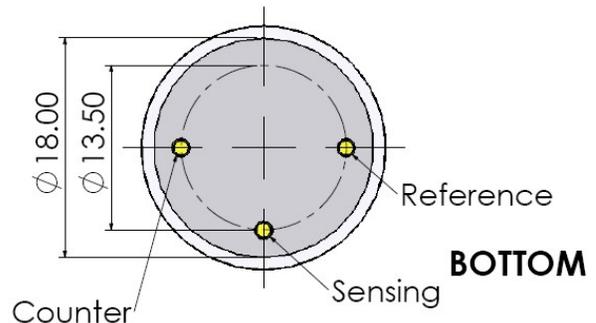
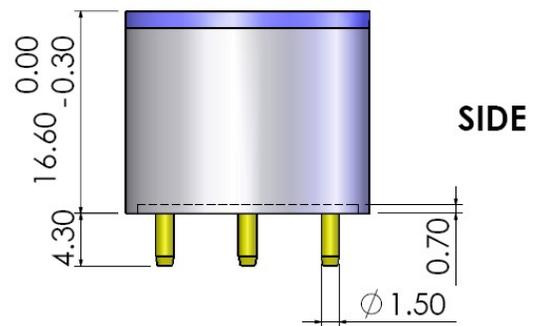
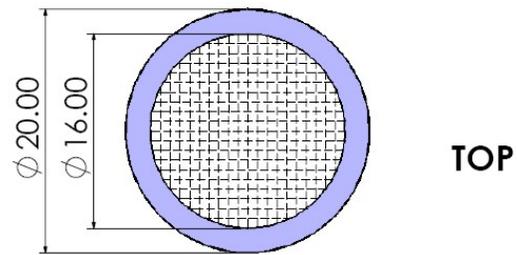
GAS	Concentration (ppm)	Sensor Response (As ppm NO2)
Carbon Monoxide	300	0
Hydrogen Sulfide	15	-1.2
Sulfur Dioxide	5	-5
Nitric Oxide	35	0
Chlorine	1	-1

### Important Note

Do not solder to the connector pins as this may damage the sensor and thereby invalidate the warranty.

Details on recommended connector pins can be found in the Frequently Asked Questions within the Gas Sensor section of the e2v website.

### OUTLINE



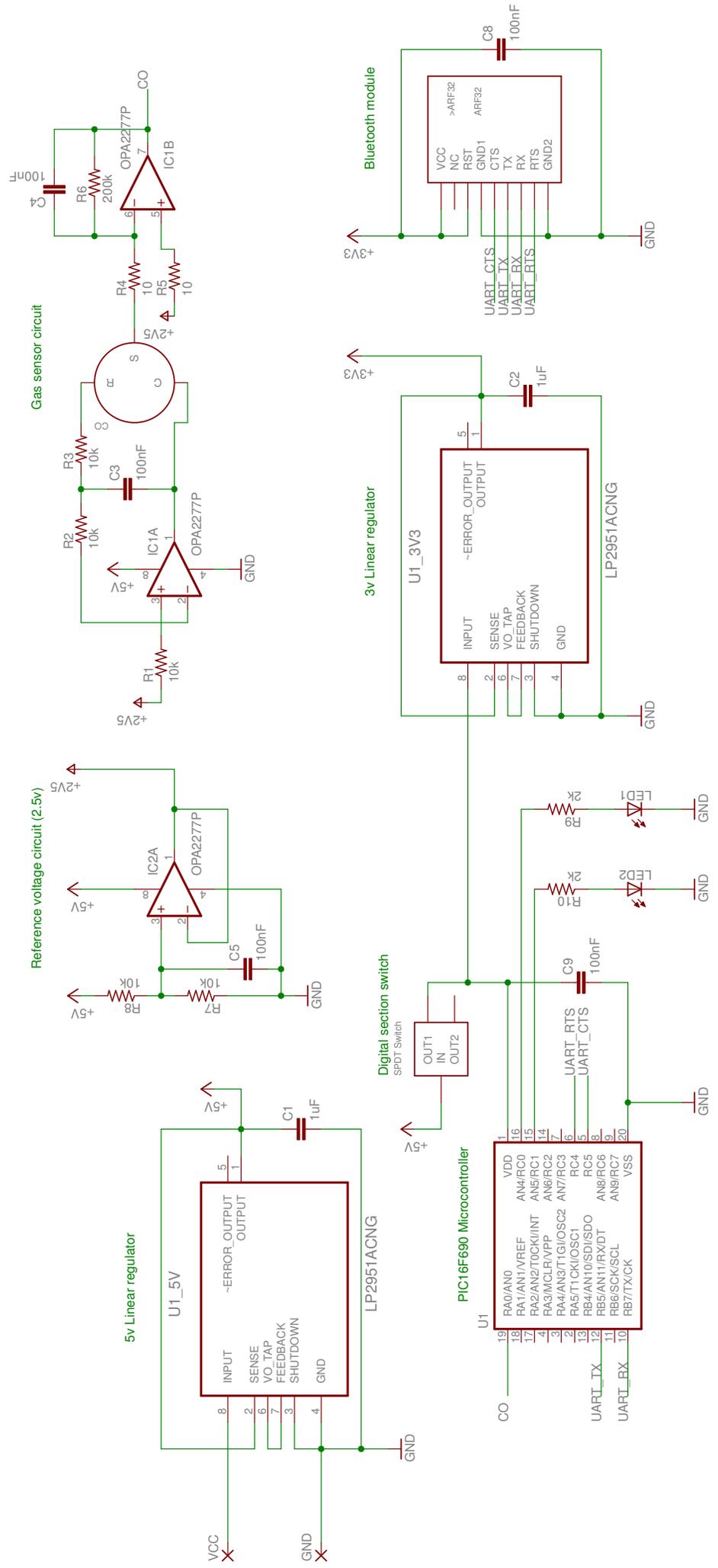
All dimensions in mm.  
 All tolerances  $\pm 0.15$ mm unless otherwise stated.

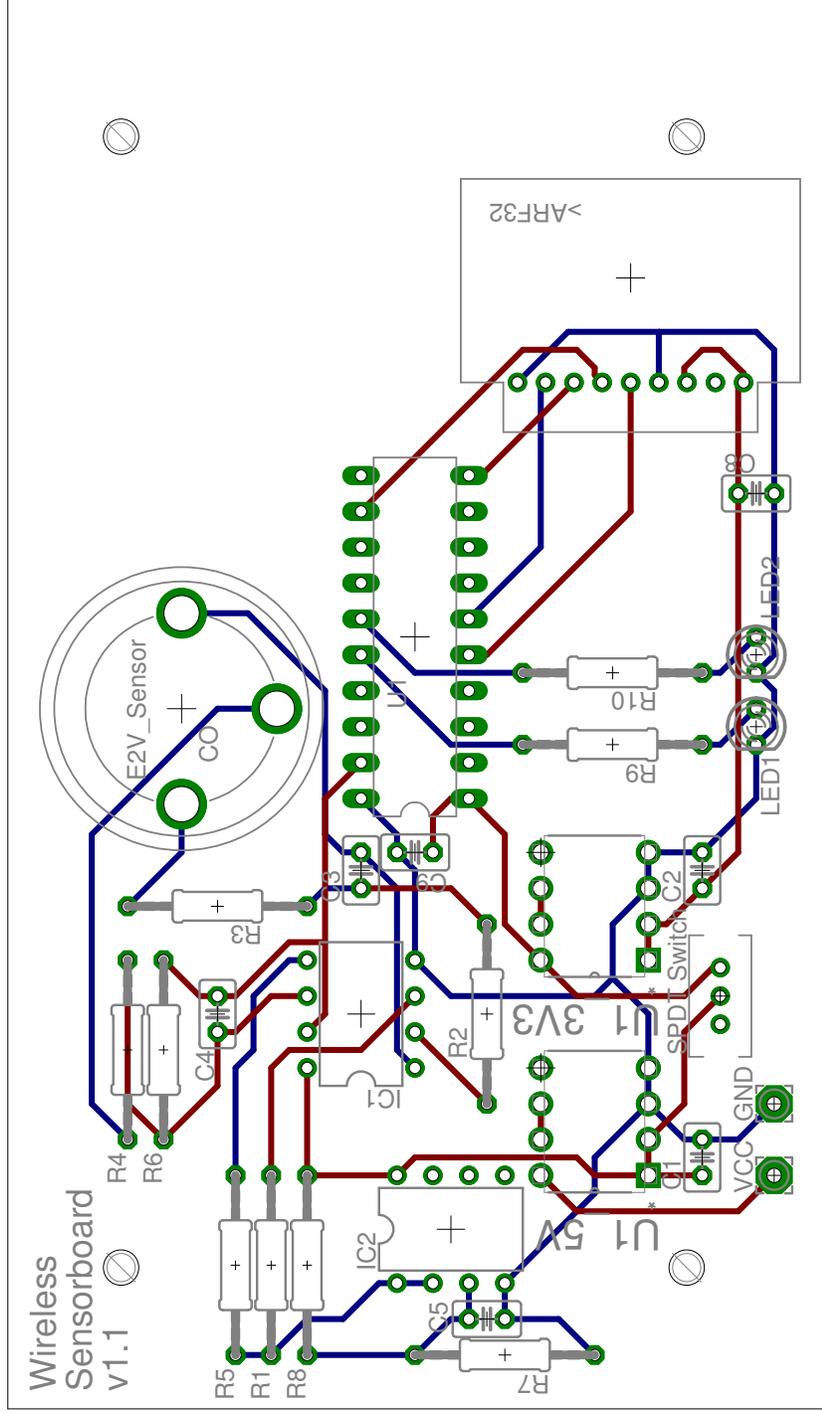
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## 4 Calibration Equations

$$CO(ppm) = \frac{1}{S_{CO}} \left( \frac{V_{out} - V_{ref}}{R_{gain}} - A \right) \quad \text{Equation 4-1}$$

$$NO_2(ppm) = \frac{1}{S_{NO_2}} \left( \frac{V_{out} - V_{ref}}{R_{gain}} - B \right) \quad \text{Equation 4-2}$$

\*Vref = 2.5V

\*Rgain = 100Kohms

	Sensitivity (S <sub>CO</sub> )	Offset (A)		Sensitivity (S <sub>NO2</sub> )	Offset (B)
CO Sensor1	73.99	-99.29	NO2 Sensor1	290.58	-6.5014
CO Sensor2	68.33	-69.541	NO2 Sensor2	335.39	48.77
CO Sensor3	75.61	-79.126	NO2 Sensor3	459.12	21.915
CO Sensor4	72.24	-88.667	NO2 Sensor4	374.94	60.384
CO Sensor5	65.486	-94.654	NO2 Sensor5	608.99	204.55
CO Sensor6	79.641	-85.714	NO2 Sensor6	432.63	46.98
CO Sensor7	72.333	-105.94	NO2 Sensor7	567.25	206.98

Table 4.1 Calibrated Sensitivity Factors for CO and NO2

**\*\* Calibration results and Analysis for Sensors 1-4 were extracted from my Thesis B report, new results for the calibrated Sensor 5-7 were appended.**

```

/*=====
Sensorboard for 4th yr thesis
Developed for the PIC16f690
Matthew Kelly: z3251873
Started: 22nd February 2012
Latest: 8th October 2012
=====*/

#include <htc.h>
#include "delay.h"

__CONFIG(INTIO & WDTDIS & PWRTEN & MCLRDIS & UNPROTECT \
& UNPROTECT & BORDIS & IESODIS & FCMDIS);

/*=====
|Main Function |
=====*/
void main(void) {
int resultCO_H = 0;//To be used to store ADC conversion result
int resultCO_L = 0;//To be used to store ADC conversion result
int deviceID = 101; //Device ID
int ver      = 100; //Code version

/*-----
|Initialisations|
-----*/
//Microcontroller inits
TRISA = 0b00000011;//Set RA1 & RA0 as input (NO2 & CO)
TRISB = 0b00000000;//Set all PORTB as outputs
TRISC = 0b00000000;//Set all PORTC as outputs

//ADC inits
ANSEL = 0b00000011; //Set AN(7->0) as analogue inputs
ANSELH = 0; //Dont wish to use AN(11->8)
ADCON1 = 1; //Set ADC clock at F.osc/8
VCFG = 0;//Set voltage reference, if = 1 then RA1 = Vref

ADFM = 0;//Set A2D format as left justified:
//ADRESH = [MSB][bit][bit][bit] [bit][bit][bit][bit]
//ADRESL = [bit][LSB][n/a][n/a] [n/a][n/a][n/a][n/a]

//ADFM = 1;//Set A2D format as right justified:
//ADRESH = [n/a] [n/a][n/a][n/a][n/a][MSB][bit]
//ADRESL = [bit][bit] [bit][bit][bit][bit][LSB]

ADCON0 = 1; //Turn ADC on, disable (ADCON = 0) to save power
DelayUs(5);//Need 4us for ADC aquisition time, function param = 5->255

//EUSART inits (for bluetooth)
//RB6 = SCK      RB7 = TX
TXSTA = 0b00100100;//Transmit enable, Asynchronous, High baud rate = Fosc/[16(n+1)]
RCSTA = 0b10000000;//Enable serial port, disable receiving
BAUDCTL = 0b00000000;// 8-bit autobaud disabled

//Desired baud rate = Fosc/[16*(n+1)] = 9600 (baud rate of BT module)
//SPBGR = n = (Fosc/BaudRate)/16]-1 = 25.0416, ~25 with 0.16% error
SPBRGH = 0;//Upper 8 bits of baud rate register
SPBRG = 25; //Lower 8 bits of baud rate register

RC5 = 0; //BT CTS
RC4 = 0; //BT RTS

RC1 = 0; //Warning LED
RC0 = 1; //Activity LED

DelayMs(200);//Wait for uart module to ready

/*-----
|Program loop |
-----*/
while(1){

//CO AQUISITION
ADCON0 = 0b0000011; //Start conversion of AN0
while(ADCON0 == 0b0000011){

```

```
    //waste time until conversion is done (ADCON0 = 0)
}
DelayUs(10); //Need at least 8us before next acquisition
resultCO_H = ADRESH; //Set the result to send as the upper 8 ADC bits
resultCO_L = ADRESL; //Lower 2 ADC bits

/*DATA SENDING from PIC TX (RB7) to bluetooth RX*/
TXREG = 0xFF; //First start byte 255
DelayMs(5); // wait for transmit to finish

TXREG = 0x00; //Second start byte
DelayMs(5); // wait for transmit to finish

TXREG = ver; //Code Version
DelayMs(5); // wait for transmit to finish

TXREG = deviceID; //Send device ID
DelayMs(5); // wait for transmit to finish

TXREG = resultCO_H; //Send sensor data
DelayMs(5); // wait for transmit to finish

TXREG = resultCO_L; //Send sensor data
DelayMs(5); // wait for transmit to finish

//Warning light at 75% of max range
if(ADRESH >= 0b11000000){
    RC1 = 1;
} else{
    RC1 = 0;
}

DelayMs(70); // Make total loop take about 100ms

} //End program loop

} //End main function
```

```
1 %Data gathering/plot for Wireless BT Pollution sensorboard
2 %Displays Real-time and Cumilative plot
3 %4th year Thesis project
4 %Matthew Kelly UNSW z3251873
5 %Last updated 25/09/2012
6
7 %% Bluetooth serial initialisation
8 s = serial('COM8','BaudRate',9600);%Set to relevant COM port
9     buffsize = 20; %Input buffer size
10     set(s, 'InputBufferSize', buffsize);
11 fopen(s);
12
13 %% Settings
14     samples = 100;           %Samples to display on screen at a time
15     wait = 0.1;             %Time to wait inbetween samples (seconds)
16     sumTime = 0;           %Sum time between all samples
17     Tscale = samples*wait; %Set timescale for x-axis
18
19     %Change values below depending on sensor used
20     nAppm = 75.61 * double(10^-9);%Nanoamps per ppm sensitivity of sensor
21     Ioffset = 79.126 * double(10^-9); %Current offset of sensor
22     Rgain = 200000;         %Value of the gain resistor
23
24     Vcc = 5;                %Microcontroller supply voltage used
25     Vref = 2.5;             %Reference voltage
26     steps = 1024;          %Steps based off the ADC resolution (10bit = 2.^10)
27
28     BTdata = 0;
29     boardnum = 0;
30     CO_result = 0;
31
32
33     %% Figure setup
34     ppm1 = zeros(samples, 1);
35     ppm2 = zeros(samples, 1);
36     time1 = -99:1:0;
37
38     ppm1_log = [0];
39     ppm2_log = [0];
40     time1_log = 0:wait:(length(ppm1_log)*wait);
41
42     %Set figure
43     fig1 = figure('NumberTitle','off',...
44         'Name','Sensorboard measurements');
45
46     % Set axes
47     axes1 = subplot(2,1,1);
48     set(axes1, 'Parent',fig1,...
49         'YGrid','on',...
50         'YColor',[0.4 0.4 0.4],...
51         'XGrid','on',...
52         'XColor',[0.4 0.4 0.4]);
53     title(axes1, 'Real Time PPM plot','FontSize',15);
54     xlabel(axes1, 'Last 100 Samples','FontSize',12,'Color',[0 0 0]);
55     ylabel(axes1, 'PPM(CO)', 'FontSize',12,'Color',[0 0 0]);
```

```
56     hold on;
57
58     axes1_log = subplot(2,1,2);
59     set(axes1_log, 'Parent',fig1,...
60         'YGrid','on',...
61         'YColor',[0.4 0.4 0.4],...
62         'XGrid','on',...
63         'XColor',[0.4 0.4 0.4]);
64     title(axes1_log, 'Cumilative plot of all PPM data','FontSize',15);
65     xlabel(axes1_log, 'Time(Seconds)','FontSize',12,'Color',[0 0 0]);
66     ylabel(axes1_log, 'PPM(CO)', 'FontSize',12,'Color',[0 0 0]);
67     hold on;
68
69     %Setup Plot
70     plot1 = plot(axes1,time1,ppm1,...
71         'Marker','none',...
72         'Color','green');
73
74     plot1_log = plot(axes1_log,time1_log,ppm1_log,...
75         'Marker','none',...
76         'Color','green');
77
78
79     %% Main loop - Collecting & Displaying Data
80     count = 1;
81     while(1) %to break out press ctrl+c, or close figure window
82
83         tic        %Used with toc to take time between samples
84
85         %Read in whole input buffer
86         BTdata = fread(s, [buffsize,1]);
87         i = 1;
88
89         %Poll input buffer until a 255 is read
90         if(size(BTdata) ~= [1,0])%If buf not empty
91             while(BTdata(i, 1) ~= 255 )%Cycle through until start byte found
92                 i = i + 1;
93             end
94         end
95
96
97         %Check for second flag byte
98         if(BTdata(i+1, 1) == 0)
99
100             %Read in microcontroller code version
101             microVer = BTdata(i+2, 1);
102
103             %Read in board number
104             boardnum = BTdata(i+3, 1);
105
106             %Read in CO_data value
107             CO_H = BTdata(i+4, 1);
108             CO_L = BTdata(i+5, 1);
109             CO_result = bitshift(CO_H, 2) + bitshift(CO_L, -6);
110
```

```
111     %Get & Scale CO data from quantisation level to PPM
112     if(CO_result ~= 0)
113         %Scale data from level to voltage
114         CO_result = (double(CO_result) * double((Vcc / steps)) - Vref);
115         %Scale from voltage to current
116         CO_result = ((CO_result / Rgain) - Ioffset);
117         %Scale from current to ppm
118         CO_result = (CO_result / nAppm);
119     end
120 end
121
122 %Put data into the arrays
123 ppm1(samples, 1) = CO_result;
124 ppm1_log(count) = CO_result;
125
126 %Plot realtime data
127 set(plot1, 'YData', ppm1);
128 ppm1 = circshift(ppm1, [-1 0]);
129
130 %Plot continuous data
131 %time1_log = 0:wait:((length(ppm1_log)-1)*wait);
132 sumTime = sumTime + toc;
133 time1_log(count) = sumTime;
134 set(plot1_log, 'XData', time1_log);
135 set(plot1_log, 'YData', ppm1_log);
136
137 pause(wait);
138 count = count + 1;
139
140 end
141
142
143 %% Finish and close ports
144 fclose(s);
145 delete(s)
146 clear;
147 clc;
```