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Chapter 1

Introduction

Earth, our home planet, is the only known place in the universe that is affirmed to host life [10]. Our life on earth is characterized by three components, air, land, and water. Each element has its special property and is required in its proper proportions to maintain the healthy life of all living beings [10]. However, industrial development and other manmade activities create an imbalance in the natural environment. The process of making environment unsuitable and unsafe for the living condition by introducing substances that are harmful to the surroundings is called pollution [11].

Pollution changes the quality of the environment and is transboundary, as they travel thousands of miles [10]. The introduction of harmful solid, liquid, or gaseous substances from human activities into the environment changes the quality of the surroundings that we live in [11]. The presence of pollutants in the environment makes an adverse impact on human health and surrounding [12] [13]. Many types of pollutants contribute to global warming and climate change which are the major issues tackled by environmental scientists these days. Out of different types of pollution, anthropogenic or human-influenced air pollution plays a major role in climate change as well as in international public health issues [11].

Air contamination can be referred to as to the release of pollutants into the environment that is unfavorable to human wellbeing and the planet in general. According to the State of Global Air [14] the air pollution is a complex mixture of gases and particles whose sources and composition vary over space and time.

The degrading quality of air over a region can be directly related to the development of industries. Contamination of air is a matter of serious concern and society is often unaware of the impact that it causes to human health as well as to the surroundings. The World Health Organization (WHO) reported that the death rate estimates are around 7 million every year as 9 out of 10 people breathe polluted air [15]. This has led many motivated individuals like researchers and communities to work towards creating awareness among the people.

There has been an enormous number of studies done to understand air pollution. Most of them involved in observing one or two pollutants of interest that are dominant in the area of measurement. Other works are on improving the quality of the collected data, and also on effective visualization. In our research work, we have tried to create a complete system that measures a set of pollutants, and the data collected from the system are calibrated for improving the data quality. The calibrated data is then visualized using a software tool. In this way, we have tried to simplify the complexity of measurements for laypersons who have interests in monitoring air pollution. This approach requires having a combined background in electronics and advanced computer skills to develop such a system.

In the following section, we will discuss the background to introduce my research work and how air pollution is being currently measured in Prince George.

1.1 Background

The success of the Industrial Revolution and urbanization led to the development and growth of the economy, society, and large scale industries. This involved the use of more mechanization and the introduction of new technologies that led to the release of harmful pollutants into the environment. The introduction of a variety of pollutants into the environment created an imbalance in the ecosystem throughout the world [11].

The declining quality of air has changed from a local issue to an international public health issue. The use of coal as an energy source in industries for example in Europe and

North America contributed to black smoke pollution [16]. Coal was not just used in industries but also in houses for heating in winter which made the pollution even worse [17]. These emissions resulted in serious health impacts on residents in urban areas that increased the mortality rate during the 19th century.

One such important event in the history of pollution is the great smog of London which killed as many as 12,000 people, mostly infants. This was caused due to the combination of cold weather with smoke and lasted for several days [18]. There was a string of similar events reported in New York, England, and other parts of the world around the same time. With several incidents contributing to the global environment, pollution led to the development of various private and government entities for ensuring air quality.

Governments along with these environmental agencies established legislation like the clean air act, the motor vehicle air pollution act, air pollution control acts for a better quality of air. Apart from that, they took the initiative to monitor air pollution by installing systems that could measure the concentration of pollutants and could give warnings to the public as well as industries regarding how polluted the atmosphere is.

1.1.1 Existing Environmental Monitoring station

Government and environmental agencies are making an effort to install monitoring stations for understanding air quality. These agencies monitor the 'criteria' pollutants (also called as common pollutants) along with any special pollutant that is dominant in that area. These monitoring stations are fixed in a location and are operated by environmental agencies. The stations are equipped with instruments that not only monitor criteria pollutants but also analyze other parameters like wind speed, humidity, precipitation. These analytical instruments work by the principle of sampling of the air collected from the atmosphere. There are two main methods for pollutant sampling: passive sampling, and active sampling [19]. These sampling techniques are considered as one of the most significant developments for air quality measurement and used widely for monitoring purposes.

In passive sampling, the pollutants are collected by a physical process such as diffusion through a static air layer or membrane. These pollutants in the air are adsorbed on the sampling media due to the chemical composition of the pollutants. The analysis of the pollutant on the sampling media gives the time-averaged contaminant concentration [20].

On the other hand, active sampling works with an air sampling pump which actively pulls the air through a collection device like a filter, and weighted concentration is calculated. However, these instruments have a major drawback of temporal resolution as they are large and need regular maintenance. These instruments are expensive and are financially impractical to expand to multiple stations. As an example table 1.1, gives the average estimated cost for purchasing air quality monitoring equipment produced by the US Environment Protection Agency (EPA). The FTIR in table 1.1 is the Fourier Transform Infrared spectroscopy measures multiple gases. It can be seen that cost of individual instruments for measuring the pollutants is considerably high.

Pollutant/Parameter	Estimated cost
NOx	10,4440 USD
SO_2	35,000 USD
COx	28,000 USD
Ox	6,600 USD
PM	37,700 USD
FTIR Analyzer	100,000 USD

Table 1.1: Estimated cost of air quality monitoring equipment [1]

As a result of the high cost, only a few monitoring stations are installed for an area. Thus, we can claim that spatial resolution is limited to these conventional monitoring systems. This has led researchers and scientists to work on portable and less expensive sensor networks to understand air pollution in more detail.

1.2 Air Pollutants and Measurement Metrics

Various pollutants contribute to the contamination of the environment. These pollutants differ from region to region depending on human activities. For example, in an industrial area that manufactures products from raw materials, such as the production of iron from its ore or production of gasoline from crude oil, releases inorganic carbon compounds into the atmosphere [21]. These pollutants released from industrial activities can have a huge impact on human health as well as the ecosystem.

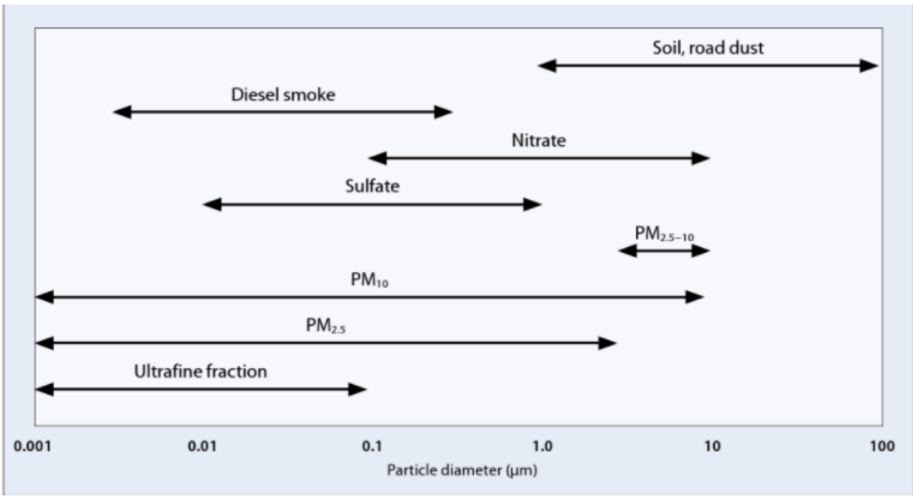


Figure 1.1: The size of Particulate Matter including PM_{10}, $PM_{2.5}$ and ultrafine particle [2]

One of the pollutants of most serious health concerns is Particulate Matter. Particulate matter is described as the particles that are formed in the atmosphere due to a chemical reaction between different pollutants in the environment [11]. These particles vary in their diameter and are measured at two levels; fine particles which are 2.5 microns or less in size ($PM_{2.5}$) and coarse particles which are 10 microns or less in size (PM_{10}). These are measured in terms of concentration in micrograms per cubic meters ($\mu g/m^3$) [22]. The fine particles are formed by foamed aerosols, metal vapors, and combustion particles. The coarse particles are formed from the break up of larger particles and contain road dust, earth crust materials, and industrial particles. The generation of both fine and coarse particles is from industrial activities, factories, construction, burning of fossil fuels, or even vacuuming. The varied composition of size can be related to the source where the particle is generated. The figure 1.1 shows the range of size that particulate matter can vary on a logarithmic scale along with the range of other components [2]. The PM_{10}, $PM_{2.5}$ along with ultrafine particles shown in figure 1.1 are the particles that cause health issues like asthma, lung disease, heart attacks, and other serious issues like cardiovascular and respiratory diseases. They are capable of penetrating through the lungs leading to cardiovascular and Chronic Obstructive Pulmonary Diseases (COPD) [23].

The next pollutant on the list is Carbon Monoxide (CO) which is produced from incomplete combustion of fossil fuels such as motor vehicle emission [24]. The majority of the CO present in the atmosphere is from road traffic and the rest is from the burning of other fuels [24]. Exposure to Carbon Monoxide (CO) which is a colorless and odorless gas, results in absorption of the gas into the bloodstream and reduces the ability of lungs to transfer oxygen which in turn affects the functionality of vital organs such as the brain and the heart [25] [26]. Another vehicle emitted gas that harms air quality is Nitrogen Dioxide (NO_2). This gas can cause adverse pulmonary disease when inhaled in high concentrations and causes illness such as wheezing, coughing, bronchitis, and increases the severity of flu symptoms [27]. The next serious pollutant present is Ground Level Ozone (O_3) which is formed from a chemical reaction between pollutants like oxides of Nitrogen or Volatile Organic Compounds (VOCs) with sunlight [28]. Respiratory issues such as a decrease in responsiveness of airways, inflammation in airways and lung infectivity occur due to exposure of high concentration of ozone (O_3) [29]. These are the most common pollutants seen almost everywhere but there are also other pollutants like Lead (Pb) or Benzene (C_6H_6) depending on the industrial activity in that area. All these pollutants can cause severe health impacts and also reduce life expectancy or even could cause death.

Based on the severity of health impact and the kind of human activities, different government agencies around the globe have taken measures to preserve the environment. Each country developed its indexes to identify the impact of pollution on the surroundings. For this, they included a specific set of pollutants that is local to the region and this varies from region to region.

For example in the United States, the Environmental Protection Agency (EPA) established the National Ambient Air Quality Standards (NAAQS) which specifies the pollutants that are harmful to the public health and environment. The NAAQS has a set of six common criteria pollutants that harm human health, the environment, or even cause property damage. The pollutants specified by NAAQS are Particulate Matter (PM), Ozone (O_3), Nitrogen Dioxide (NO_2), Carbon Monoxide (CO), Sulphur Dioxide (SO_2), and Lead (Pb).

India on the other hand measures eight major pollutants such as Particulate Matter (PM), Ozone(O_3), Nitrogen Dioxide (NO_2), Carbon Monoxide (CO), Sulphur Dioxide (SO_2), Ammonia (NH_3), and Benzene (C_6H_6) (in some places (Pb) instead). Most other countries measures a subset of these criteria pollutants, for example, Canada measures PM, O_3, NO_2, SO_2 and CO [30].

Each country has identified a set of pollutants and measurement units for these pollutants. For a layman to understand these individual measurements and its cumulative impact on the quality of air is challenging. Taking this into account, the government agencies of each country has developed their indices similar to the NAAQS for representing the quality of air. A wide range of indices have been proposed like Air Quality Health Index (AQHI), Air Quality Index (AQI), Air Pollution Index (API), Pollution Standard Index (PSI), Comprehensive Air Quality Index (CAI), Daily Air Quality Index, Common Air Quality Index (CAQI) are few used in different countries [31]. Out of all these indexes, the most common is AQI and AQHI which are proposed and used by different countries [30].

India, USA, UK, and many other countries use AQI, and Canada, Hong Kong uses AQHI. These metrics are designed by carefully examining those pollutants which are harmful to human health and the environment. The AQI is defined as a piecewise linear function of the pollutant concentration [32] and is measured using the following formula.

$$AQI = Max\{I_i | i = 1, ..., 8\} \tag{1.1}$$

where I_i is an air quality sub index corresponding each pollutant and it is computed as

$$I_i = \lceil (\frac{I_{high} - I_{low}}{C_{high} - C_{low}}) \rceil \times (C - C_{low}) + I_{low} \tag{1.2}$$

where C is concentration of the i^{th} pollutant. C_{low} and C_{high} are lower and upper concentration breakpoints of C respectively. I_{low} and I_{high}, respectively, are index breakpoints corresponds to C_{low} and C_{high}. The value of AQI varies from 0 to 400+ as shown in Figure 1.2 and is color-coded to show the quality of air in the atmosphere.

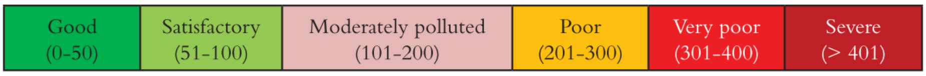


Figure 1.2: Air Quality Index (AQI) [3]

In past Canada used the USA's AQI for understanding the air quality. Due to some concerns raised by provincial and municipal health authorities, Health Canada along with Environment Canada developed AQHI to make the public aware of the quality of air that surrounds them and how it affects their health. The basis of generating this newer tool is to understand how air quality affects human health and this is achieved by statistically linking the pollutant data with the outcomes of human mortality [6].

Initially, it was based on five major pollutants $PM_{2.5}$, O_3, NO_2, SO_2, and CO initially and later the last two pollutants were dropped from the calculation as they were identified to contribute less in predicting health effects. The following formula computes AQHI.

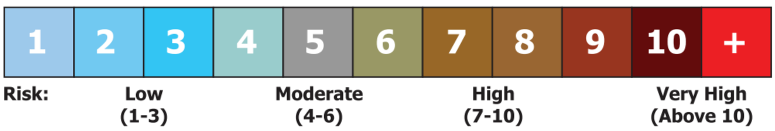


Figure 1.3: Air Quality Health Index (AQHI)

$$AQHI = \lceil (\frac{1000}{10.4}) \times [e^A - 1] + [e^B - 1] + [e^C - 1] \rceil \tag{1.3}$$

where $A = 0.000537 \times$ concentration of O_3 (ppb), $B = 0.000871 \times$ concentration of NO_2 (ppb) and $C = 0.000487 \times$ concentration of $PM_{2.5}$ (ug/m^3). The value of AQHI can belong to any one of the four health risk categories as shown in figure 1.3: AQHI value from 1 to 3 - low health risk, value between 4 to 6 - moderate health risk, AQHI value from 7 to 10 - high health risk, and value above 10 - very high health risk.

The value of AQHI gives the risk level based on the exposure to pollution level as people get affected when they are exposed to pollution. In this way by identifying the value of AQHI the people can avoid the short-term exposure to pollution and help to build community with better air quality.

1.3 Air Quality measurement in British Columbia (BC)

Air quality monitoring in BC is measured by the provincial government, Metro Vancouver along with Environment Canada and regional districts. There are around 150 stations for air quality measurement and these are maintained by Ministry of Environment (MOE) and some industrial staffs with permit. The main pollutants of interest in BC are Carbon Monoxide (CO), Nitrogen Dioxide (NO_2), Ozone (O_3), Particulate Matter ($PM_{2.5}$ and PM_{10}), Sulphur Dioxide (SO_2), and Hydrogen Sulphide (H_2S). These pollutants are measured in three ways: continuous monitoring, non-continuous monitoring, and mobile monitoring [33].

1. Continuous monitoring: This is an automated mode of measurement in which air quality is measured by drawing air through tubes. The collected air is automatically monitored, measured, documented, analyzed and validated using Data logger. This data is then further checked for any errors and made available to public in an hourly manner in the current data page. The popular instruments used and parameters measured by the province are given in the table 1.2.

2. Non-continuous monitoring: The non-continuous monitoring is also called as manual sampling. In this method the field technicians assigned by the ministry staffs collects the air sample by placing filters or canisters for a discrete period of time (such as one, three, or six days). The sampling follows strict rules set out by the Ministry of

Instrument name	Pollutant/Parameter measured
Tempered Element Oscillating Microbalance (TEOM)	Particulate Matter ($PM_{2.5}$ and PM_{10})
Beta Attenuated Monitoring (BAM)	Particulate Matter ($PM_{2.5}$)
UV Photometry	Ozone (O_3)
Chemiluminscence	Nitrogen Dioxide (NO_2)
UV Fluorescence	Sulphur Dioxide (SO_2)
Pulsed Fluorescence	Total Reduced Sulphur (TRS) or Hydrogen Sulphide (H_2S)
Nondispersive Infrared Photometry	Carbon Monoxide(CO)

Table 1.2: Instrument used and parameters measured in BC province

Environment (MOE). The collected sample is then sent to the certified labs where it is weighed and examined to understand the content. After all the careful identification the information is uploaded to the database of MOE. The manual instruments used to collect the sample values are Single Channel 16.7l/m (PM2.5 and PM10) monitors, Dichotomous (Coarse and Fine PM) monitors, Speciation monitors, Volatile Organic Compound monitors (VOCs), PAH monitors, and Passive samplers.

3. Mobile monitoring: The last method for collecting the data is by installing monitoring instruments in a large vehicle or an airplane. These instruments move around for s short period collecting data around areas where fixed monitoring is not available. One such air quality monitor is Mobile Air Monitoring Laboratory (MAML) [4] build on Ford F550 chassis which can measure both continuous and non-continuous measurement.

Figure 1.4: The Mobile Air Monitoring Laboratory Vehicle [4]

The common air pollutants measure by MAML are black carbon, Sulphur Dioxide, Nitrogen Dioxide, Carbon Monoxide, Ozone, and Particulate Matter (PM). It also measures meteorological data like wind speed, wind direction, temperature, and humidity. The collected data is then analyzed and transferred to the database of ministry.

1.3.1 Pollution Monitoring System in Prince George

The city of Prince George is located in the central part of the British Columbia province at the junction between the Nechako and Fraser rivers. The city has reported bad air quality due to the forest fires, road dust, geographical location, transportation, and other factors. The air quality of an area can be directly related to human activities within the physical environment [11]. For this reason, it can be seen that there is a huge variation in the distribution of pollutants from region to region. For example; the presence of an industrial source such as a pulp mill in and around this area can highly affect the quality of air. Other factors include topography, atmospheric condition, and magnitude of emission from sources [34].

Figure 1.5: Map showing the location of the eight monitoring station in Prince George [5]

Having considered all these factors over the years in Prince George, Government agencies along with industrial partners funded the installation of eight fixed monitoring stations to measure the dominant pollutants in the area [35]. Figure 1.5 shows the layout of the eight monitoring stations located in the region as reported in the air quality report of 2016 [5]. The data collected from these stations are monitored by the Prince George Air Improvement Roundtable (PGAIR) which includes the Ministry of Environment (MOE), the Ambient Air Quality Monitoring Working Group, and other volunteers.

Of the eight monitoring stations installed, there is a core station that measures all six pollutants which includes Particulate Matter ($PM_{2.5}$ and PM_{10}), Total Reduced Sulphur (TRS), Sulphur Dioxide (SO_2), Nitrogen Dioxide (NO_2), Ozone (O_3). The other stations only measure certain pollutants or meteorological data [5]. The core station which is called the Plaza 400 monitoring station is located downtown and here the air quality can be recognized as a combination of industrial, commercial, and residential emissions [35]. This station contains several instruments such as API model 400 ozone monitor for ozone, API NO_x monitor for Nitrogen Dioxide, SHARP model 5030 for $Pm_{2.5}$), TEOM 1400a analyzers for $Pm_{2.5}$ and $Pm_{2.5}$, and TRS samplers for Total Reduced Sulphur [5] [35]. These data are available in the Ministry Of Environment (MOE) [36] website and the data can be accessed and downloaded by the public.

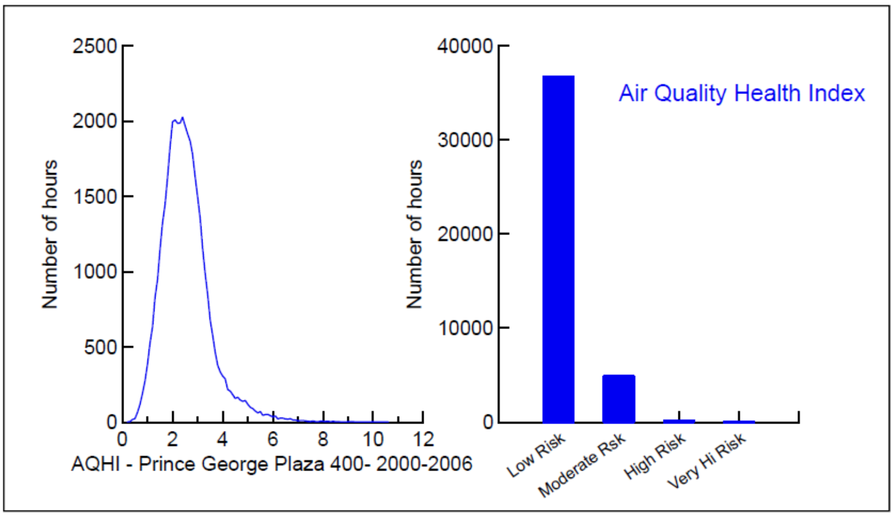


Figure 1.6: AQHI distribution in Prince George between 2000 to 2006 [6]

The collected pollutant value is then used to calculate the AQHI value that does not remain the same throughout the year. It changes from 1 when the air quality is good to 10+ at the time of unusual activities like a wildfire. This can be seen in figure 1.6 that shows the frequency of occurrence of indexes and the related health issues in town. It can be seen that between the year 2000 to 2006 the AQHI value varied mostly between 0 to 6 which is from low health risk to moderate health risk. During that time high AQHI value is very rare and can be accounted to less than 1% of time [6].

1.4 Motivation

One of the important components in dealing with the issue of air pollution is to increase awareness among the public about the current situation and its impact so that they can act on it. The conventional method of monitoring air quality with the help of a few expensive and stationary monitoring systems typically installed by government agencies may not be effective. To achieve the goal of public engagement, pollution monitoring must become part of daily activity for everyone. For that, the devices to monitor pollution must be small, portable, inexpensive, and part of a regional, national, and global system. With the technological advancement of low-cost computing, communication, and sensing devices, and the revolution of open source software [37], we believe it is possible to build a pervasive air pollution monitoring system with the available sensors from the market and open-source software. Now the question is how to design such pollution monitoring systems faster and make them accessible to as many people as possible.

Achieving the above-stated goal requires a suitable system framework that can help to accelerate the process of the design and implementation of an air pollution monitoring system using the off-the-shelf hardware and building open source tools for representing the data collected from the sensors. Some recent attempts to build low-cost air pollution monitoring systems have been done, however, none of them are simple and easily replicable. This thesis is an attempt to fill that gap by first proposing a simple and comprehensive framework and then demonstrating its feasibility and use by creating our own low cost and easy to use a pollution monitoring system that is operational in our lab. We have also added a step of calibration by implementing a web-based tool to ensure that we measure high-quality data. Our contribution is a step towards inspiring and motivating not only the public to use the device but also enable many amateur electronic hobbyists to buy and construct the hardware and download the associated software to build their pollution monitoring device.

1.5 Thesis Contribution

There are three major contributions from the thesis:

1. Air pollution monitoring system: The system itself which measures the pollutants from the atmosphere. This includes the sensors with the processor and the data transferring module. We believe that this could be a way to show that a low-cost system could be used for data collection.

2. Air pollution visualization software: The next major contribution is the software that could be used for data visualization. The main idea is to make the collected data user-accessible and hence we came up with the idea of building the complete tool from the scratch as the other available tools in the market are costly.

3. Calibration tool: Development of a web-based tool for sensor calibration to ensure the quality of data obtained from the sensor system.

1.6 Structure of the Thesis

The rest of the thesis is organized as follows. Chapter 2 focuses on a review of related work for different methods of understanding and detecting pollution. This is divided into four main categories and work done in each category is explained further. Next, in Chapter 3 the design and implementation of a pollution monitoring system and the visualization tool are explained. To test the accuracy of collected data to the original data we have implemented a calibration tool by linear regression which is described in Chapter 4. In Chapter 5, we present an analysis of the results obtained from the system. Finally, in Chapter 6 the conclusions and directions for future work are discussed.

Chapter 2

Literature Survey

Development of Wireless Sensor Network (WSN) is considered as one of the matured innovation in the field of electronics. The miniaturization of the components has allowed the user to explore applications in various fields such as health care, military applications, traffic control, monitoring, and data collection [38] [39]. Out of all the applications, urban air quality monitoring has gained a lot of attention as it is one of the major issues faced by society today. While reviewing the related work, we found out that there are various methods used for understanding pollution. This could be classified into four based on literature as follows [40] [41].

1. Vehicle-based sensor network
2. Wearable sensor network
3. Community sensor network
4. Static sensor network

Further we will be highlighting the important research done in each of the above four categories and will be classifying to which category our work falls.

2.1 Vehicle based sensor network (VSN)

In recent times, the number of private vehicles on the road has increased in proportion to the increasing population around the globe [42]. Even though the increase in the number of automobiles is one of the major factors that is contributing to the increase in pollution, certain researchers took this as a medium for measuring air pollution data. In this category of work, the vehicles (like buses or cars) are installed with a portable, low-cost sensor to obtain spatially resolved data.

One of the best ways to study the quality of air is by collecting fine-grained data also called 'micro-climate monitoring'. However, with the existing monitoring system being bulky and expensive it is impossible to obtain spatially resolved data. To solve this issue, in 2009 a group of researchers used mobility as a method and proposed a vehicular wireless sensor network [7] that measures the changes in concentration of a single pollutant measurement (Carbon Dioxide in this case) by mounting the sensor node onto a vehicle. The system is equipped with a Carbon Dioxide (CO_2) sensor, a Global System for Mobile (GSM) module, a GPS receiver, and a ZigBee module to create an intra-vehicular network. The collected data is transferred through GSM short messages to the server and is displayed on Google Maps for results. The architecture of the VSN is shown in the figure2.1.

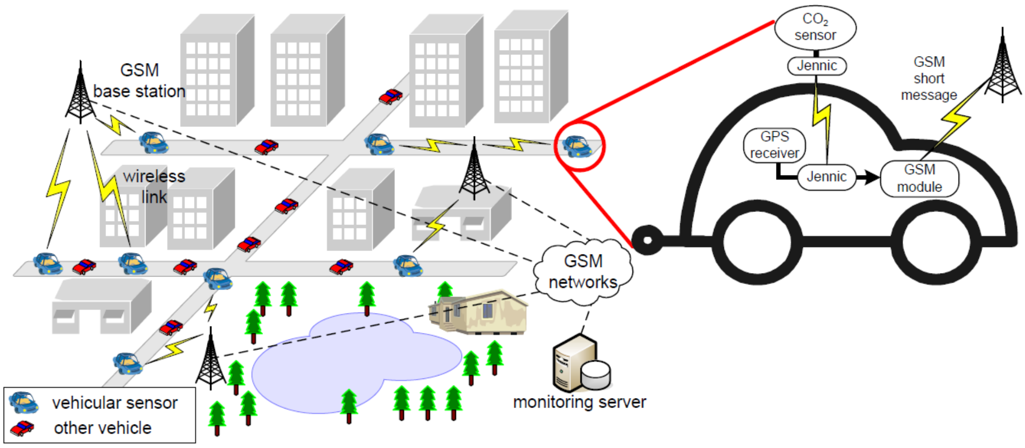


Figure 2.1: Architecture of Vehicular based sensor network [7]

This work faced two network-related drawbacks. Firstly there was a duplication of air pollution data as the number of vehicles in a given area changed dramatically from time to time and secondly, to reduce the data transfer in an area with many sensor nodes at the same time by exploiting opportunistic communication. These two problems were later addressed in 2011 [43] by designing two message-efficient algorithms. The first algorithm works by dividing the sensing field into a fixed number of grids and each grid was allocated with a particular reporting rate which is called dynamic reporting rate to reduce communication overhead. The second algorithm allows the sensing nodes to communicate with each other and find out their reporting rate and opportunistically transfers the collected data.

Volgyesi et al. [44] proposed the Mobile Air Quality Monitoring Network (MAQUMON) that measured three pollutants, Ozone (O_3), Carbon Monoxide (CO), and Nitrogen Dioxide (NO_2). The air pollution system is mounted on a car and is powered by a Li-ion battery whose battery life is limited to a few hours. It is equipped with a GPS module for determining the location and the collected data is transferred to a laptop through a Bluetooth module. When the system is in coverage of a Wi-Fi network the collected data is transferred to a web server and visualized in sensor map web application in the form of contour maps.

The data collection that involves more frequent and spatially dense pollutant measurement is called a fine-grained approach. In [45], the vehicular-based approach of measuring fine-grained air quality in real-time was demonstrated. To increase the spatial density the study proposed two data collection models one for public transportation infrastructure and the other for a personal sensing device. A Mobile Sensing Box (MSB) was installed in public transit buses which contained the microcontroller (Arduino), sensors for measuring Particulate Matter (PM), Carbon Monoxide (CO), a GPS module and a cellular modem. The module was powered through the bus batteries and the collected data were transferred to a server and visualized using Google Fusion tables interfaces. In the second framing, a Personal Sensing Device (PSD) that included an air quality sensor was installed in cars and connected via Bluetooth to a smartphone. This gave the user information about the air quality while driving through a specific area. The data obtained from both the framing models were compared using linear regression and the results showed a positive linear relationship between the data sets. Even though there was a high correlation seen between the two sets of data there was no comparison with the local reference data to understand the accuracy of the system.

A similar technique of data collection like in [45] can be seen in wireless sensor deployment [46] that proposed the idea of placing the sensor nodes in public transport buses to obtain real-time data of pollutants. The system here is divided into sensor node and sink node in which the former collects the data from the environment and the latter aggregates the data from the sensor node and transmits to a server via a long-range radio band. These sink nodes are either installed in a T-junctions or an X-junction of the city where most of the buses cross. The data is transferred at a regular interval of time and can be analyzed instantly. However, the paper did not discuss the collection of data and failed to provide the quality of collected data.

A research group from Japan, Shirai et.al [47] proposed an effective method to acquire air quality data in an urban areas in which the air pollution system has a sensing unit kept on a public vehicle like a garbage truck and garbage patrol vehicle which moves in and around the city. The main focus is on pollutants like Particulate Matter (PM), Carbon Monoxide (CO) and Sulphur Dioxide (SO_2), and is also aided with GPS module. To remotely monitor the sensing conditions and to check for maintenance, a control center tool has also been developed. It consists of a map that tracks the route of the vehicles and the sensor data acquired by each vehicle. A monitor was developed along with the system to send the users the collected data. It estimates the amount of pollution inhaled by the user like one in [45] which by acquiring the user's location from the mobile application and mapping it to the location-sensors value which has been already computed. It also considers the respiratory volume of the user to estimate the pollution inhalation.

Another mode of transportation that was taken for understanding the air quality was the public bicycle system. The bicycle borne sensor [48, 49] deploys a system equipped with an exhaust gas sensor, Particulate Matter (PM) sensor, GPS module, and a microprocessor. The system collects data along with the location from the GPS module and is stored in a micro storage chip. The system is powered with the help of Lithium polymer batteries. When the subscriber returns the bicycle to the dock station the data is transferred to the data center via the Bluetooth module and is then visualized using the 'Baidu' heat map.

In [50], Unmanned Aerial Vehicle (UAV) is used as a medium to understand air quality. In contrast to the work done in [7, 43–49] this work focused on six different pollutants that contribute to Air Quality Index by mounting the sensor board on the flight. The flights are carried out in 30 days with 20 minutes of monitoring. Along with the sensor board, a smartphone is attached that collects data from the air sensor by establishing a Bluetooth connection. The collected data is transferred to air quality analysis software that will display the real-time monitoring value along with AQI value.

The existing studies in this section show that collecting data using VSN supports micro-climate monitoring. The advantage of having spatially resolved data is that it helps to understand the trends of pollution in a better way. At the same time, the probability of having redundant data due to traffic congestion or duplication of data is high. Another concern is that there was no effort taken to understand the quality of data obtained. The main idea of deploying the system is to educate citizens and make them aware of the quality through the indexes. The efforts to calculate AQI or AQHI is not taken as a priority except in [50]. The representation of these indexes will make people aware of the air quality but most of the work in this category has failed to bridge the data gap.

2.2 Wearable sensor network

The individual effect of pollutants on health depends on the extent to which a person is exposed to the polluted environment. The understanding of the health effects could be achieved by observing the exposure-response relationship [51] this will give an idea about the amount of pollutants inhaled by an individual. This could be achieved by using a wearable sensor which helps to understand the effects of individual impact when exposed to polluted air.

Research was done in this section mainly focuses on improving the understanding of personal health and exposure to air pollution [52]. One such development is Mypart [23] from the University of California, which is a wrist-worn particle sensor that measures particulate matter of 10 microns or less. The design of MyPart is based on a traditional laser-based photodiode system with improvement in airflow to remove light leakage, integration of structural design and circuitry for ambient visualization, BLE transceiver for low power networking, and also a mobile application for visualization. Two main issues tackled by MyPart is accuracy and calibration of sensor which no existing consumer sensor has addressed.

Another related work is 'Eco-mini' [53] which is a wearable stand-alone device for clinical use that measures Volatile Organic compounds (VOCs), sound level, air quality, temperature, and humidity values. This system is based on a low power microcontroller (Atmel Xmega 128k) and consists of a GPS module for position identifying and a Bluetooth module for data transfer. They modified the webserver which was developed on a simple javascript application. The next wearable work is 'citisense' [54] which is a system attached to a bag stripe which measures air pollutants like Nitrogen Dioxide (NO_2), Carbon Monoxide (CO), and Ozone (O_3) along with environmental parameters such as temperature, humidity, and barometric pressure. The collected data from the sensor is processed by the microcontroller (ATMEGA1284p) and transfers the data using a Bluetooth module to a smartphone which does the data storing, analysis, and data aggregation. The collected data is then transferred to a back-end webserver from where the user can get a personalized view of their data. They also developed a citisense android application that runs on the smartphone.

In [55], the research group in the US developed an expressive T-shirt called 'WearAir' which indicates the measured Volatile Organic Compound (VOC) through expressive patterns. The T-shirt is designed with a metaphor of a car emitting gases with four vertical arrays of LEDs which shows different frequencies depending on the concentration of VOC gas in the surrounding. When the wearer is exposed to dense VOCs the LED will blink rapidly. The authors of [56] developed a novel system consisting of several sensors that give real-time feedback on an individual's exposure dose. This consist of arm sensors, chest sensor or even wrist sensors which measures various pollutant concentration (CO in this case) and transfers to an android or ios application via Bluetooth. They also calculate the inhaled dose of pollutants by calculating the volume of air inhaled into a person's lung per minute through an algorithm developed in [57]. The inhaled dose of the pollutant was calculated and compared during various activities like jogging, bicycling, and driving.

There are also wearable sensor projects initiated in Vancouver in association with the University of British Columbia like TZOA [58] that can be clipped to the clothing and measures the air quality. It mainly measures PM values and display in an application. These devices decrease the gap between individual and their understanding of the polluted air. In NewYork a striking project named 'Aircasting' [59] provides the health and environment data using the android 'Aircasting app'. The 'Aircasting' [60] platform includes a palm-sized air quality monitor that measures $PM_{2.5}$, relative humidity, and temperature. The outside air is drawn through a sensing chamber and the particles are measured through the light scattering method. It also includes a LED wearable apparel named 'Air casting luminescence' [61] that illuminates LEDs according to the obtained sensor measurement; varying from red for high intensity, then orange, then yellow, and finally green for low intensity.

The emergence of such wearables makes individuals be more cautious about their health and encouraged people to stay fit. At the same time, the public is not aware of these devices and does not prefer wearing T-shirts or carry a device for understanding the impact of pollution. Another issue to be focused on is the cost and stability of connection due to which the measured data values won't be able to visualize.

2.3 Community sensor sensor

The development of portable sensor devices has paved way for a novel paradigm for monitoring the pollution known as crowdsourcing or participatory sensing. This gives an opportunity for any citizen to collect data and transfer it to a common platform like a web interface. The collected data from the participants give a spatiotemporal view of the effect of pollution [62]. In Sydney, a low-cost participatory system is deployed named 'Haze-watch' [63] for monitoring pollution in urban areas. In this, mobile sensor units were attached to vehicles, and collected data were transferred using Bluetooth to a mobile application which tags its location with date and time information. This data is then sent to a cloud-based server that stores data and applies interpolation models [64] to generate Spatio-temporal estimates. Then using a web application the geo-referenced data is depicted as a contour map.

Intel has developed a prototype named 'Common Sense' [65] which is based on mobile participatory sensing [66] that enables citizens to collect relevant data and involves in the decision making process. The system includes a handheld device that measures a couple of pollutants and uploads the value for visualization over the web using Bluetooth or GPRS radios. This work was further tested by deploying it on a municipal fleet of street sweepers in the city of San Francisco [67]. Another community-driven sensing developed is 'OpenSense' [68] which focuses on the utility of data by giving an idea about how the data collected from sensors needs to be consumed. They have provided two use-cases first one is smart healthcare which by giving alerts on identifying the pollution-induced diseases (like asthma, particle allergies, etc.) and next is urban planning by identifying polluted areas and identifying alternative routes. The system is deployed on mobile vehicles and stationary stations in Switzerland and the collected data is pipelined to a Global Sensor Network (GSN) from where the streamed data is processed and represented. In [69] an outdoor participatory monitor was introduced called 'GasMobile' by connecting a low-cost ozone sensor to an android smartphone. The collected data from the sensor is transferred to the phone and from which it is visualized using an application as well as a webserver. They have also implemented calibration procedures to the low-cost sensors and the work claims to have high accuracy when compared to static measurement. The above-mentioned research work in 'OpenSense' and 'GasMobile' have made an opening for further participatory sensing research in Switzerland supported by Samsung called 'Exposuresense' [70] that monitors user activities like walking, running, etc., from smartphones and understanding their exposure from obtaining data from the already installed 'OpenSense' and 'GasMobile'. Their main idea here is to make use of the available smartphone for next-generation healthcare.

The growth of the Micro-Electro-Mechanical System (MEMS) and Wireless Sensor Network (WSN) have made difference in the way how data is collected and understood from the physical world. 'G-Sense' [71], for Global-Sense, is a work initiated from the University of Florida in which they combine features of sensing platform applications like Location-Based Services (LBS) for tracking and location identification, Participatory Sensing (PS) for determining pollution index, and other environmental data, and Human-Centric Sensing (HCS) for health-related data for a specific group of users. The sensors collect the data and sends to a first-level integrator where all the data gets collected and from there using a data transport network it is transferred to the server that stores and performs data processing. It is from the server where the data visualization takes place which reports the data. Later there was another work which is considered to be the subset of G-Sense and named as 'P-Sense' [72] or Pollution-Sense. The architecture of this system is based on G-Sense in which external sensors are integrated into an Arduino development board. In this, the data collection is based on Participatory Sensing (PS) and the goal here is to provide government officials, doctors, and community developers with data so as to get a deeper understanding. They have also pointed out the research-oriented challenges that need to be addressed when building a community networked system like security, privacy, data visualization, and working towards achieving them.

The work discussed in this category seems to be more promising but at the same time the quality of data obtained, getting public involvement for data collection, and privacy issues [40] are a few challenges researchers are trying to work towards it. The cost of maintenance in such a community network in case of any damage is a crucial factor.

2.4 Static sensor network

In this category, the system is kept at a fixed location like traffic lights, street lights or any planned areas [41] which collects the pollutant values and transfers it to a visualization platform where the users can view it instantly. These systems are inexpensive and can be easily replicated or replaced. The system can be used for measuring either indoor or outdoor pollutants. The already existing station based environmental monitoring system is complex, bulky, and expensive; hence there is a need to develop a portable and low-cost environmental monitoring system. There is various noticeable research work done under this category and I have briefed relevant ones.

The Integrated Environmental Monitoring System (IEMS) [73], integrates different environmental detection sensors in a single system, and data from this system is used for processing and visualization. IEMS consist of Integrated Environmental Monitoring Device (IEMD) which consists of Microcontroller units, sensors, wireless communication module. They developed the Handheld Remote Control Panel (RCP) for the system which is an android application that acts as an interface for the device control and handles the data exchange between IEMD and Web Server. Finally, the webserver that provides real-time data visualization and data analysis. These systems were placed on bus stops, bridges, and even in the construction sites. Another research team from Mauritius developed a Wireless Sensor Network Air Pollution Monitoring System (WAPMS) [74] that designed a data regression algorithm named Recursive Converging Quartiles (RCQ) to remove duplicate data and then calculate AQI values. The array of sensor nodes collects the pollutant data and transfers it to cluster heads where the RCQ is applied to improve efficiency and alleviate the congestion problem. From the cluster head, the data is sent to the server and represented using line graphs for each area.

'AirSense' [75] is an excellent approach to assess indoor air quality. The author tries to introduce the idea of indoor air quality to the society by proposing a system which measures indoor pollutants. The system works through electronic sensors that are coupled to an Arduino (processing unit). The system not only extracts the data but also provides its users with very effective visualization and analysis of the data. The researchers have done an excellent job of developing this robust system that would sense the pollution and provide education and awareness among the users. This system has made use of some machine learning algorithms to predict the pollution sources and forecast their behaviour so as to provide intelligence to the system. The system has also got a smartphone application that gives the users a very effective interface for visualizations and understanding of the data. In [39] a different group of researchers from China developed the system 'Air-Sense' to monitor and predict the quality of air based on the ZigBee network. The system uses four different types of sensors, respectively are humidity, temperature, $PM_{2.5}$, Total Volatile Organic Compound (TVOC includes the general organic gases), and a ZigBee trans-receiver for communication with network nodes. The prototype is tested for different areas in the house. It collects data in real-time and using Bayesian mathematical statistics it predicts how accurate is the collected value to the standard value predicted by WHO.

Another static work that focuses on indoor air quality is demonstrated in [76] in which the main focus is to understand the pollution in an office environment where the pollution is triggered by the electronic devices and machines. In this, the primary pollutant measured is ozone which is mainly emitted from a photocopier machine. The system is designed into different nodes where the sensing node contains the Arduino which processes which collects the data from the ozone sensor. The measured data is transferred through a Bluetooth link to a gateway node from where the data is formatted as IP packets and forwarded over the Ethernet network to the processing node. The data is saved in the database and using a 2D graph the concentration gets visualized. A research group from Harvard University developed a wireless networking testbed called as 'CitySense' [77] in which multiple environmental sensors are attached to street lights. These sensors were deployed in Cambridge and data was uploaded to the server using mesh networking like RoofNet [78], TFA [79], and CUWin [80]. Using a Web-based interface the data can be pulled from the server and made available to end-users. The main feature of this research work is that the sensor nodes are powered from street lights and there is no constraint about long battery life.

Liu J.H. et al [81] developed a micro-scaled air quality monitoring system for understanding the CO emission from vehicles by integrating the sensor nodes with a gateway. The data collected from the sensor is transferred to the gateway using a ZigBee communication link and from here meteorological data and collected sensor data are forwarded to a central system through short message service via GSM. This centralized control system is supervised by the LabVIEW [82] programming which helps in storing the data into the MySQL database. They deployed the system on the main roads of Taipei city and obtained accurate values of pollutant concentration.

Our research work falls under a static sensor network in which we have tried to integrate a system that measures all the major pollutants in the city of Prince George and also providing AQHI values. Unlike the other system mentioned in the literature, our main focus is to give user-specific data for a better understanding of pollution. We have categorized the users into three; layman, data scientist and the officials. We have also tried to implement a calibration procedure to ensure the quality of data.

2.5 Summary

In this chapter, the research done in the sensor network for understanding the air quality is categorized into four. We went through the system which is attached to a vehicle for understanding the pollutant concentration and gets categorized as a vehicular sensor network. This category provides great mobility but at the same time, the accumulation of redundant data is high. The next category we mentioned is the sensors that could be worn or attached to a person. This gives a better understanding of the individual health effects of the pollutant and also the amount of pollutant inhaled. The work under this category has not gained a lot of attention as it demands the individual to carry the device. Participatory sensing is the next category in which the citizens perform the collection of data and it gets transferred to a common platform. Although the work done in this is more promising it faces challenges like privacy, data quality, and maintenance cost. The final category is in which the system is placed at a planned area and called as a static sensor network. Our research work falls under this section and we focus not just on collecting pollutant value but also on making an effective visualization to reduce the data gap for users.

Chapter 3

Calibration Of Low Cost Sensor

With the development of sensor technology for air pollution it has attracted a majority of researchers as well as common people to explore and understand more about the pollutants and its effects. This has given freedom for one to set up their own monitoring system at residences, office or even at schools. The problem with this is to identify how accurate the data collected from these commodity sensors to the reference monitoring system.

The reference system are the pollution monitoring devices that are developed to a clearly defined standard for a specific criteria pollutant [s] and has completed a rigorous testing and analysis protocol [83]. If the system is giving values which is way too different from the reference value then it brings down the advantages of this technology. This issue can be dealt through calibration which will reduce the uncertainty in data and makes the output more accurate.

Calibration can be defined as the act of evaluating and adjusting the precision and accuracy of measurement equipment [84]. If the measured output from the sensor is not equals to the actual output then it shows that there is a need for calibration. Usually all the electronic instruments are calibrated according to a particular conditions in the laboratory and acquires a certification of calibration before its sold out in the markets. Even then the measured value does not reach accuracy as the condition or the environment where it was calibrated changes that leaves the user with some raw values that gives no information. This issue was taken up and explored by a few researchers in the US Environmental Protection Agency (EPA) and suggested with three 'Straw-Man Approach' to improve the usability of such data and presented in the Air sensor Workshop [85].

The first approach was by a signal-based calibration technique which requires the data from the remote stations, which is the reference station, to be broadcasted to the local station where the sensor is located and will receive this data and performs a single point calibration of the response. This approach would have been easy if the sensor was already equipped with the data collection and would process automatic calibration.

The next option for calibrating is called the direct sensor calibration that involves placing the sensor in a chamber in which a known concentration of pollutant is set and response is observed. As the concentration of the pollutant is already known the output curve can be compared with it and calibrated accordingly. This is the most common method used for calibration as is often called as laboratory evaluation. Another way of approaching direct calibration is by inspecting the pre-defined response given by the manufacturer and checking how accurate the sensor is to the given concentration. In either case the calibration requires equipment and skills to give accurate concentration value.

The last option is by secondary data normalization in which the concentration values of the pollutant from the low cost sensor is normalized in accordance with the federal reference method (FRM) or federal equivalent method (FEM) analyzers. This approach is cost effective when compared to the other techniques and is less complex. This could be achieved by the use of a linear mathematical equation model that will convert the non-calibrated data into data of an acceptable form. The linear relationship equation $y = mx + c$ where m is the slope and c is the intercept of the sensor raw data is compared with analyzer data and a relationship pattern is found out from this. The drawback of this is that the sensor data does not always give a linear response and thus not applicable for all the curves.

Even though these 'Straw-Man Approach' was defined well it was still hard to implement it practically. This eventually led to the development of the 'Air Sensor Toolbox' by the Environmental Protection Agency (EPA) [86] which introduced a tool called 'Macro

Analysis Tool' (MAT) for performing comparisons of air sensor data with reference data and interpreting the results [87].

3.1 Calibration Procedure

The Air Sensor Toolbox provide guidelines for researchers, citizen scientists and developers with working of low cost sensor and its calibration to give more insight about air quality [88]. The Air Sensor guidebook [87] provides a three step procedure for calibrating a sensor:

1. Comparing the data from the low cost sensor with a reference instrument.

   This means the data collected from the sensor system should be compared with the data from an already calibrated system which is placed by the local authority. This type of comparison is called as 'collocation' and in order to collocate, first find out where the reference system is placed and get access to the data from these system. After getting access to these system place the sensor system at the same level as the standard reference. Once this is done the data collected from both the system can be downloaded in the desired format.

2. Creating a calibration curve with the help of Macro Analysis Tool (MAT).

   The relationship between the response of an analytical instrument to the concentration or amount of an analyte introduced into a known instrument is referred to as the "calibration curve" [89] and is obtained by linar regression [90]. Linear Regression establishes relationship between two variables one is the independent variable which will be on the x axis and the dependent variable in the y axis by drawing a straight line [8]. The MAT tool by EPA is used for drawing the calibration curve and will give an error function as output. This error function is an equation which can be used for calibrating the sensor.

3. Repeating the calibration periodically.

This procedure of calibration should be done periodically as the performance of instruments changes often. There will be changes in the equation and graph each time and this should be noted so as to get accurate value.

3.2 Macro Analysis Tool -MAT

The development of MAT tool gives a huge reliefs for the researchers in calibrating sensor data. This is an Excel based user-friendly macro tool that compares sensor data with reference data [91] even if measurements weren't recorded at precisely the same time, or were collected at different time intervals, such as 1-minute versus 5-minute intervals [92].

The user needs to insert the data from the sensor into the sensor page of the tool and the values from the reference station is inserted into the reference page of the tool. After these values are inserted the details of pollutant, time interval, measurement units and data completeness (amount of usable data obtained) needs to be added in the set up page of the MAT. After all the required fields are filled the output page as shown in the figure 3.1 shows the two sets of data being compared as per the control panel setting made in the tool [91]. This output page basically gives the statistical comparison of two different data sets. From this page it could be seen that the date and time stamps are averaged to a single value for both the system. There is another column in the sheet which is the invalid data points that gives the total number of non validated data points during the observed time. This non validated data points occurs due to either the fault by instrument or it could be the fault in reading by MAT or it could be even due to unacceptable range specified by the user.

Another output page provided by the tool is correlation graph which plots a graph between the reference monitor and the sensor data as in the figure 3.2. The graph drawn will be a scatter plot and a line called as 'slope-intercept' will be drawn through the data points and is represented simply by the equation $y = mx + c$. This equation represents the average behavior of the sensor data (vertical axis, represented by y) compared with the reference data (horizontal axis, represented by x) [91]. The slope of the graph shows the similarity or dif-

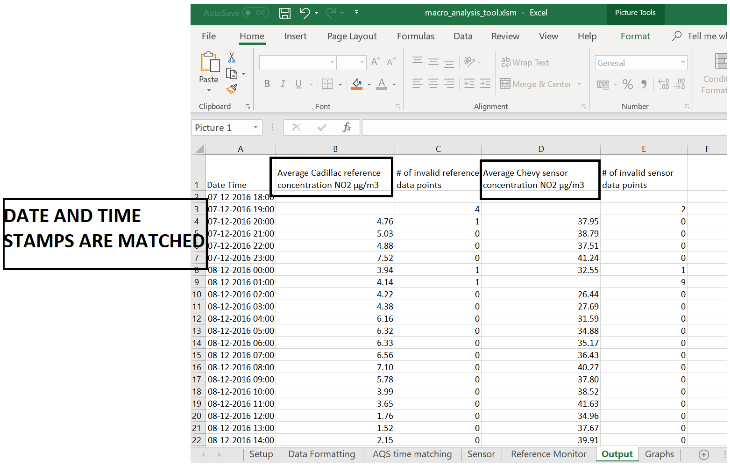


Figure 3.1: MAT Output

ference in sensor measurements when compared with the reference instrument, on average.

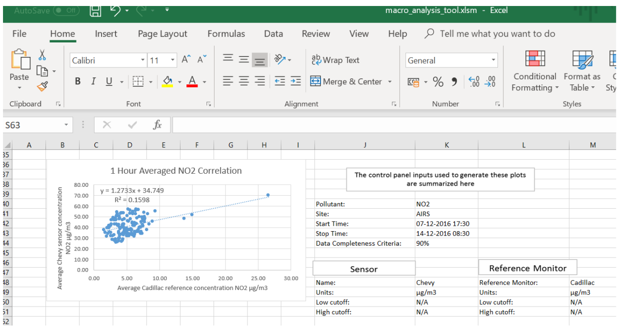


Figure 3.2: Correlation Graph

The tool also generates a coefficient of determination (also known as correlation coefficient in statistics) or R-Squared (R^2) shows how close the value is to the slope-intercept line. The value ranges from 0 to 1 and the closer R^2 is to 1, the stronger the agreement between the sensor and the reference data [93]. Along with these output the tool also generates a time series output graph which will show the concentration of pollutant for both the system as in the figure 3.3

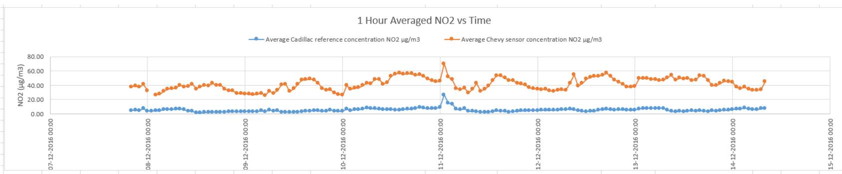


Figure 3.3: Time-Series Graph

From the Time-Series graph it could be seen how the closely value from two different system is related to. Having included all these functionality in the tool gives a strong solution for the calibration. The development of the tool was a year-long project of EPA with other community group (Clean Air Carolina) and one tribal nation(Eastern Band of Cherokee Indians).

3.3 Linear Regression

Calibration can be done through different statistical methods and the most popular approach is Linear Regression method. In statistics, the term regression is used to describe a group of methods that summarize the degree of association between one variable (or set of variables) and another variable (or set of variables) [90]. Linear Regression establishes relationship between two variables one is the independent variable which will be on the x axis and the dependent variable in the y axis by drawing a straight line. If there are many observations and is plotted as a scatter plot then a line called as regression line as in the figure 3.4 could be drawn through it by Least Square method.

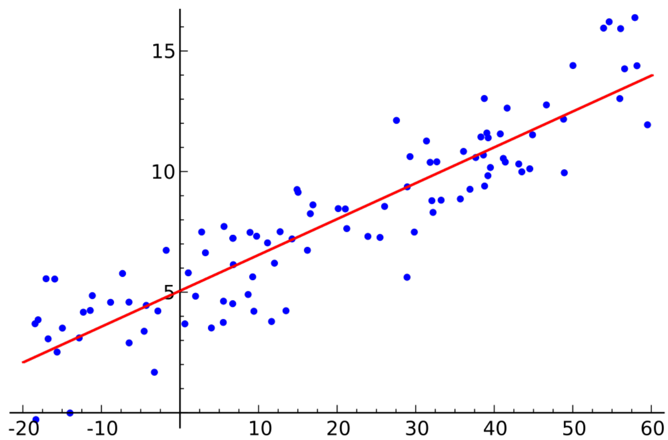


Figure 3.4: Linear Regression Model [8]

The method of Least Squares is a procedure to determine the best fit line to data [94] by minimizing the errors between the observed value and the actual value. This method considers that, for each value of x, there is a sub-population of y values normally distributed, that the means of all the sub-populations of y lie on the same straight line and all the sub-populations of y values have equal variances [95] [96]. The line drawn will have a slope m and is given by the formula

$$m = \frac{\sum_i[(x_i-\bar{x})(y_i-\bar{y})]}{[\sum_i(x_i-\bar{x})^2]} \text{ [97] [98] [90]}$$

where m is the slope, x_i and y_i are the reference and observed data values, $\bar{x}$ and $\bar{y}$ are the mean values of the data. The mean values will act as the centroid of the regression line and it has to pass through these points. The intercept equation c is

$$C = \bar{y} - m\bar{x} \text{ [97] [99]}$$

On getting the slope and intercept value the equation of line can be found. Once the Regression line is drawn, to find out how much the data is scattered and to what extend, correlation coefficient (R^2) is used. In other words R^2 gives the measure of degree to which the values of x and y are linearly correlated [97]. The equation for finding the regression value is

$$R^2 = \frac{\sum_i[(x_i-\bar{x})(y_i-\bar{y})]}{\sqrt{[\sum_i(x_i-\bar{x})^2[\sum_i(y_i-\bar{y})^2]]}} \text{ [97]}$$

The range of value for R^2 is between 0 to 1 and closer the value is to 1, the stronger the correlation between the two data. All these equation can be easily calculated with the help of Excel and thus all these equations are integrated to the MAT tool.

3.4 Framework

The developed MAT tool solved and provided an efficent method for calibration of low cost sensor. In our work we have implemented Linear Regression [90] in an IoT platform. The platform gives the user to input the value collected from the reference system as well as any low cost sensor system.

These data uploaded to the online platform should be .csv (excel) file format. The user will have four options to enter manually in which the reference data file, sensor data file

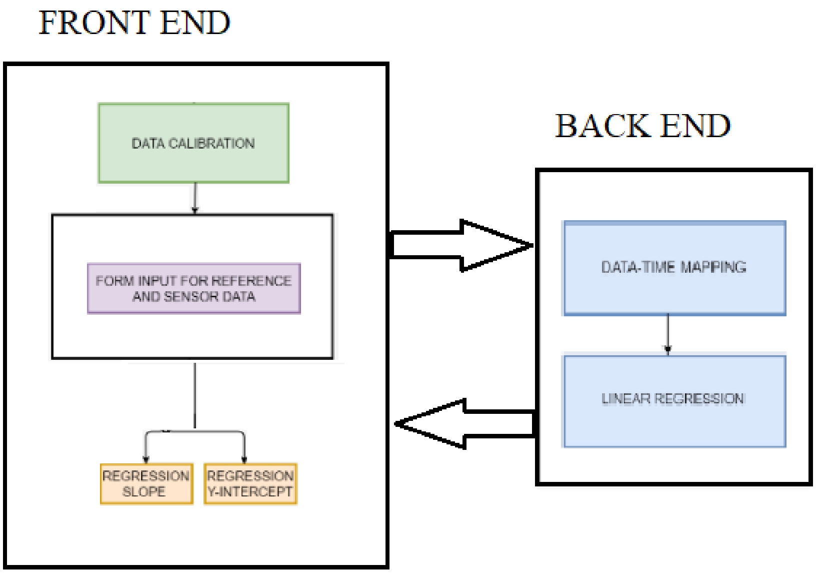


Figure 3.5: Framework of Calibration tool

along with the date and time will be entered. Once the required data is updated the regression analysis takes place and it generated the regression slope and y- intercept as the output. This output regression equation is used as the calibration equation. This tool can be accessed globally from anywhere in the world. This tool has followed the same calibration procedure as that of the MAT tool in which the data from both the system is compared and generates a calibration curve. The calibration equation which is the output is used in the system to obtain the calibrated value.

3.5 Summary

In this chapter we have discussed about how we are dealing with accuracy and precison of our low cost sensor. We have talk about the MAT tool used for calibrating the measured data from the system and implemented the IoT version of the tool. Further in the next chapter we will be talking about the design and development of the air pollution monitoring system and also the software aspect.

Chapter 4

Design and Implementation of Air pollution Monitoring System

The use of complex, expensive and stationary monitors for collecting and analyzing the pollutant data began soon after the 1970 Clean Air Act came in action [100]. Ever since then researchers and environmentalist were interested in studying the pollution data and its effects. This became even more popular after the development of the low cost, easy to use, portable sensors came in markets [101]. In our research work, we have attempted to fill the gap for understanding the quality of the data obtained from the sensors by comparing it with the orginal monitoring system. In this chapter, I share my hands-on experience in the design, development, integration, and operation of the air pollution system using the available air pollution sensor in the market. We have also build a visualization tool for effective data representation which is explained at the end of the chapter.

4.1 Design Goals

For the development of a reliable and simple pollution monitoring system, we have researched and came to conclusion about certain factors that need to met so as to make the system efficient. These design goals are very unique to our work and are listed as follows:

1. Sensor Selection

   There are different kinds of sensors available in the market for measuring a particular kind of pollutant. Selecting the right kind for obtaining accurate data was one of the challenging task. The Air Sensor Guidebook by US Environmental Protection Agency (EPA) [87] provided a lot of guidelines which we followed before purchasing the sensor. One of the main factor that we looked in the sensor was accuracy of collected data. Keeping in mind, we researched different available sensors in market and concluded with the ones which we felt that would meet our demand.

2. processor Selection

   In order to make the system functional there should be a processor. Choosing which processor to work on was the next task which we again delt by answering the questions like 'whether we wanted our system to be simple or complex?', 'whether it is an open-source in hardware and software?','the ease of programming','how easily can the processor be available?','how much is the cost?'. This gave us a clear idea for selecting the processor.

3. Communication Module

   Once the sensors and processor were identifed we need to find out a way how the raw data from the processor should to be transferred. We wanted the system to be wirelss and for that either bluetooth or Wi-Fi module can be used. We also wanted instantaneous data representation and Wi-Fi module served well for that purpose.

4. Easy Integration

   The integration of sensors with the processor and communication module is the next important factor that needs to be addressed. Some sensors can be easily integrated with any processor but others needs driver codes to be written in order to work with the processor. Also, the presence of one sensor should not affect the sorrounding sensor, otherwise will result in error values.

5. Printed Circuit Board

   The final system should be build on a printed circuit board as it is more dependable. Circuit build on basic breadboard might even come out as it is not permanently fixed and this will cause frequent breakdown. Its always easy to work on breadboard but that will be useful only for the initial set up. The system should be transformed to PCB.

6. Maintenance

   The next goal which we want to achieve was easy replication of hardware modules in case of any damage. For this we wanted the system to be a plug and play model so that in case of any hardware issue the debugging will not be challenging. We have also selected the hardware modules on the basis of their availability in the market so that replacement will be quick. The basic idea behind such a system is that the system could be used by anyone without even having dept knowledge.

7. Low Cost

   The final and the most important factor was the cost. There is a price range for the hardware modules in the market extending till $800 per module. We wanted to create a low cost system which could be affordable and will be under $400 for the entire pollution system.

4.2 Targeted Pollutants

Our surrounding is filled with various gases and will become harmful if the concentration of it increases to an undesired level. We need to carefully identify which pollutant is dominant in a particular area and select the pollutant to be measured accordingly. The main idea here is to make the general people aware about the dominant gases and the extend of health hazard caused by these gases. This can be identified through different indexes know as Air Quality

Health Index (AQHI) which is a scale from one to ten developed by health and environmental professionals [102] and Air Quality Index (AQI) which gives the level of air quality status in an area [103].

The development of such indexes by the scientists will give the general public more idea of the pollution. The main gases to be included for the measurement for the indexes are $PM_{2.5}$, O_3, NO_2, and CO along with temperature and humidity sensor for awareness. These gases are mainly caused due to industrialization, urbanization and motorization [104]. Industrial and vehicles release greenhouse emissions which are largely responsible for air pollution [105]. The sensors thus can be limited to five which will also make the system compact.

4.3 System Architecture

In this section we describe the design of the implemented air pollution monitoring system which can be categorized into system hardware architecture and system software architecture. The system is designed in such a way that it collects the data through the sensors, performs specific mathematical equation for calibration on the raw data and then transfers to the server.

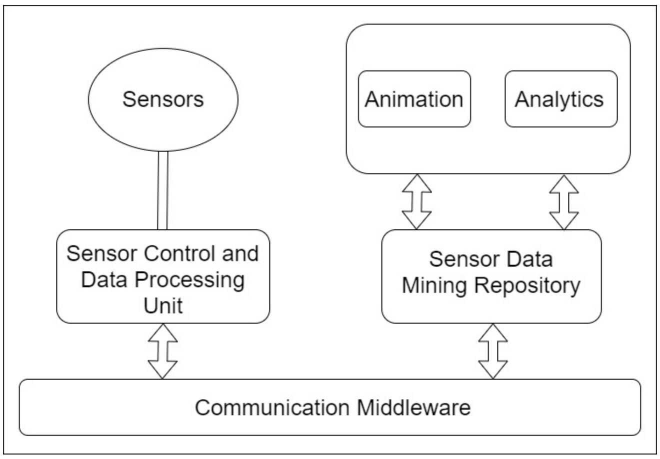


Figure 4.1: System Architecture

The hardware section includes multiple sensors, processor and also on the wireless communication module for transmitting and receiving signals. Second, we will discuss the air pollution visualization tool which mainly focuses on representation of data. The overview of the system is as shown in the figure 4.1 and each part along with the sensor specification, implementation, design will be discussed further in the section.

4.4 Hardware Architecture

4.4.1 Sensor Control and Data Processing Unit

This is the main component for pollution monitoring as it is where all the other sub-modules are connected including the communication middleware. The main function handled by this module are as follows:

1. Control the sensors in collecting data.
2. It filters and processes the collected data and forward to the server.
3. Provide the necessary voltage for all the hardware connected to it.

For simplicity and ease of programming we have selected one of the popular processor in market, Arduino Ethernet board which has ATmega328 microcontroller as shown in Fig.4.2.

Arduino is an open source physical computing platform that is divided into two parts, one is the hardware which is the board itself in which the external components are added to and other is the software which is the development environment for the processing language. It is very simple to use the board with any external devices such as sensors or actuators and is widely used by researchers. There are different features which makes arduino popular and can be listed as [106]:

1. Arduino is multi-platform and can be used with windows,mac and linux.
2. The programming is done via USB cable and not serial port and is useful as modern computers don't have serial port.

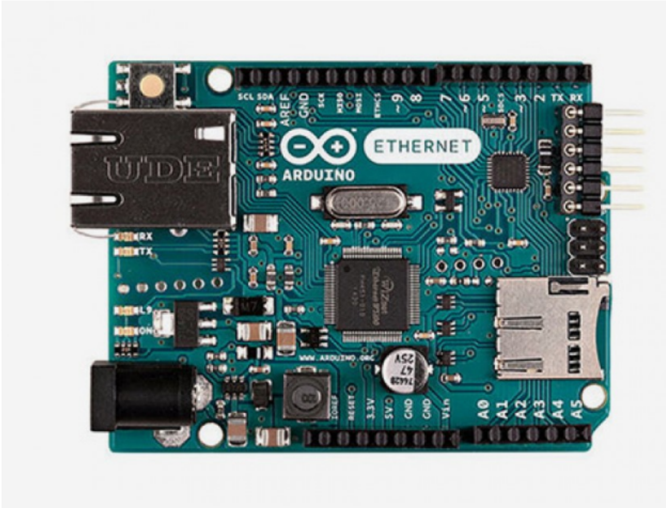


Figure 4.2: Arduino Ethernet Board

3. As it is open source hardware and software all the necessity for an external hardware to be worked on like circuit diagram, the code can be easily downloaded.

4. There is an Integrated Development Environment (IDE) which can be used as an interface for talking with the hardware and is very simple.

5. There is an active arduino forum in which many researchers or developers who are working on projects contribute their ideas and will help in trouble shooting.

6. The cost of the hardware is very cheap and will come under 60 CAD and is easily affordable.

The board can be powered either by using a FTDI cable/USB serial connector, external power supply or using an optical Power Over ethernet module (PoE). The ATmega328 has 2 KB of SRAM and 1 KB of EEPROM. The detailed specification [107] of the board is given below in the table 4.1.

Having all these specification gives the freedom for researchers to explore with different electronic devices easily. The board is programmed with the help of arduino programming language which is very close to embedded C language and it is done on Arduino development environment.

Description	specification
Microcontroller	ATmega328P
Operating Voltage	5V
Input Voltage Plug (recommended)	7-12V
Input Voltage Plug (limits)	6-20V
Input Voltage PoE (limits)	36-57V
Digital I/O Pins	14 (of which 4 provide PWM output)
Analog Input Pins	6
Flash Memory	32 KB (ATmega328P) of which 0.5 KB used by bootloader
SRAM	2 KB (ATmega328P)
EEPROM	1 KB (ATmega328P)
Clock Speed	16 MHz

Table 4.1: Technical specification

4.4.2 Sensor

Sensor networks are instruments useful to detect the conditions in remote places in the physical world in environmental monitoring applications such as pollution monitoring, transportation management, intrusion detection and many more [108]. With constant development in electronics industry, it is possible to collect data remotely and this data can be transferred to a required platform within a short period of time. There are different sensors available in market which can measure the pollutants and display the value, but the idea here is to select the one which is of low cost and also gives the most accurate values.

Having said that there is a variety of options available for sensors based on the way it measures the pollutants. One such category is Metal Oxide Semiconductor (MOS) gas sensor also known as semiconductor gas sensor, which is used to detect the concentration of any hazardous gases in the atmosphere by changing its resistance. The most popular series available in market for this category is MQ-XX sensors which is popular for its wide detecting scope, long life, stability, high sensitivity, fast response and also simple drive circuit [9].The sensing material is made up either from Aluminum Oxide (Al_2O_3) or Tungsten Trioxide (WO_3) based ceramic and has a coating of Tin Oxide SnO_2 that acts as the sensing material for the desired gas. The sensing element is heated through Platinum wires which is connected to leads made up of Nickel-Chromium, well known conductive alloy. The gas to be detected has a specific temperature at which it gets ionized and the task of the sensor is to work at that temperature. Once the gas gets ionized it gets absorbed by the sensing material which changes the resistance and inturn changes the voltage across the sensor and can be read by the microcontroller [109]. The voltage value along with reference voltage and other resistor's resistance is used to find the resistance of sensor. Once the resistance of the sensor is known then by using the sensitivity curve the concentration could be found out.

Another popularly used MOS sensor which we explored was MICS which are MEMS based whose mode of operation is similar to the above said sensor as both of them are metal oxide. Here, oxidizing gas or the pollutant gas add to the insulative oxygen species causing the resistance to increase [110]. Other than MOS sensors, we also took a look at optical sensor which are spectroscopic devices which uses light scattering principle to find the concentration of pollutants. These sensors are known for its detecting capability of particulate matter of different sizes and is one of the recent development in the field of air quality monitoring. Highly responsive, reliable and long life are the main highlights of this sensor.

Selected Sensor

After understanding the wide range of sensor options in the market the sensors were selected based on their performance, availability, ease of integration, and cost and are listed below:

1. MQ-2 Sensor: This is a a semiconductor gas sensor which has an electrochemical sensor which detects multiple gases such as Carbon monoxide, LPG, methane, and other combustible steam. The sensor is connected in series with a variable resistor to form a voltage divider circuit and the variable resistor is used to change the sensitivity. The sensitivity curve for MQ-2 is shown for different types of gases, where R_o is the sensor resistance in clean air and R_s is the sensor resistance when exposed to gas.

   From the curve in Fig.4.3, the voltage across the sensor is found out depending on which gas one wants to detect and there after using this voltage value the concentration

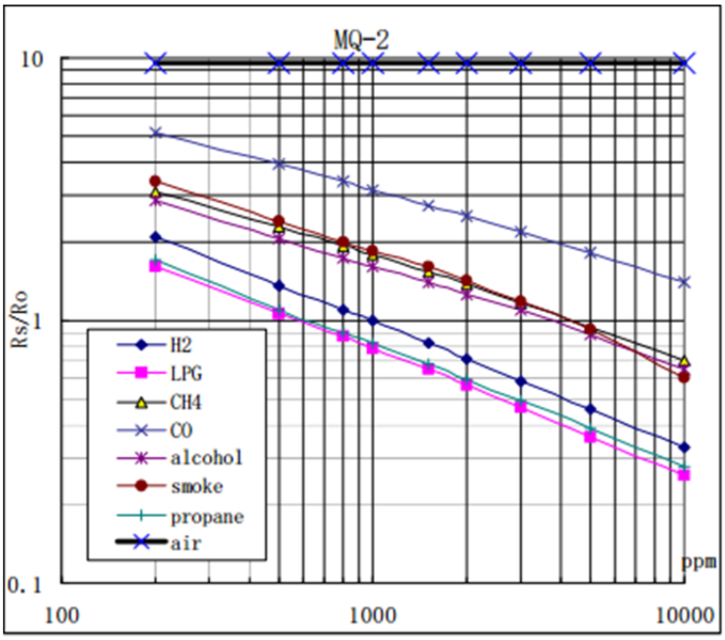


Figure 4.3: Sensitivity characteristics curve [9]

of pollutant is calculated. The range of detection of gas is from 100ppm to 10,000 ppm and has a high sensitivity and fast response time. The sensor is small and portable and provides integration in famous MCU platforms like arduino, raspberry pi etc.

2. MQ 131: Another MQ-XX series sensor that we used for the system is for ozone. The working of the sensor is similar to MQ-2 sensor. It decreases the resistance when exposed to ozone and becomes more conductive when exposed to large concentration of the gas. This can be used to measure the concentration of ozone in air. The detecting concentration scope is from 10ppb to 2 ppm of ozone and also has a fast response time and long life.

3. MICS-2714: This is a robust MEMS sensor used for the detection of Nitrogen dioxide (NO_2). The detection range is from 0.05 to 10 ppm and has a response time of 10 seconds. The sensor is comparatively small and of low cost.

4. PPD42NS Particulate sensor: The sensor detects the particulate matter through light scattering mechanism and consists of infrared LED positioned in forward angle to a photo diode. As soon as there is a variation in light density, the photo diode detects

this and changes the current from the diode [111]. The circuit generates a measurable signal known as Low Pulse Occupancy (LPO) which is proportional to PM concentration [112]. This sensor can measure both PM2.5 and PM10 concentration.

5. DHT11: This a very low cost sensor available in market for temperature and humidity measurement and has a calibrated digital output. The measurement range for temperature is from 0 degree to 50 degree Celsius. The device can be integrated to almost all platforms of Microcontroller and is considered to be the best choice for many applications.

4.4.3 Communication Middleware

The collected data needs to be transferred to a server and from there to a visualization tool so that user can understand and interpret the data. Choosing the communication middleware was a tough task as we need a stable connection that will constantly send data over the network. At first we used an ESP module for data transfer. The WiFi module, ESP8266, which is a highly integrated SOC that meets the requirement of user demand of efficient power usage, compact design and reliable performance [113]. The ESP module can be connected to a processor or it can also be flashed on its own as the module itself is a MCU unit. Unlike the other sensor modules connected to the processor which needs a 5V power supply for its working, this module needs a 3.3V for its power up. The ESP module comes along with installed firmware from AI-thinker and it can be communicated with AT commands. On typing the AT command in the serial monitor the output would come as 'OK' if there is a successful connection.

However this module failed to provide a reliable connection to the network and also it faced issues with power-up when all the sensors were connected at once. This became a challenge for data transfer and this is when we chose a more efficent and reliable module called WEMOS D1 mini. WEMOS mini is a miniature microcontroller based on ESP8266 and can be easily integrated with Arduino and NODE MCU. The development board has eleven digital input/output pins and one analog pins. The programming for the device is done through Arduino IDE and flashed with the help of a USB Micro B connector. The programming for the system was very similar to the earlier ESP module and provided a stable connection.

4.4.4 System Overview

This section will show about the integration of the above mentioned sensors with the processor. After selecting the sensors and processor for the air pollution data measurement the next task was to put together so as to make it as a working system. This step was done one at a time so that troubleshooting will be easy. The complete circuit diagram of how the components are integrated to the Microcontroller is as shown is the figure4.4. Each of

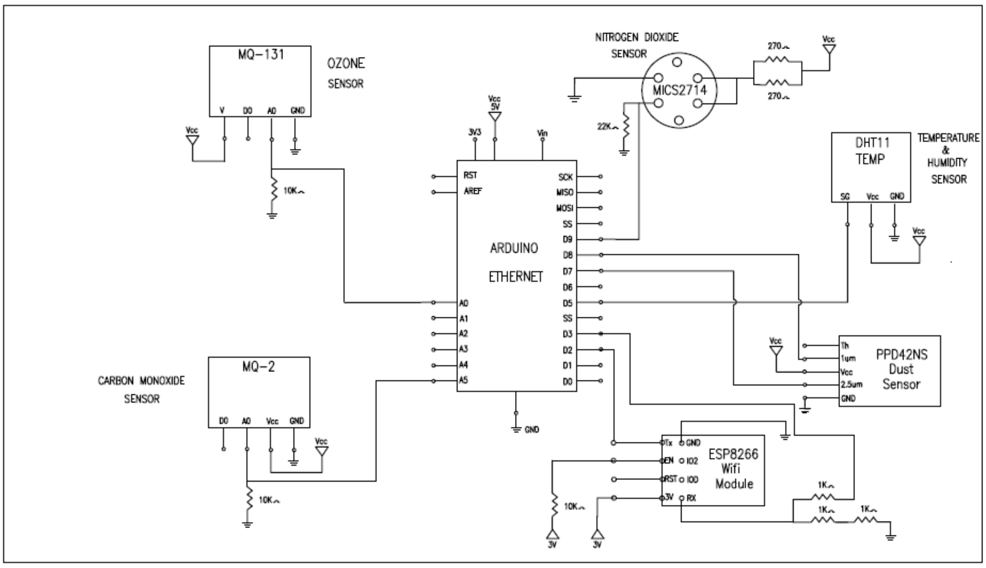


Figure 4.4: Circuit daigram of air pollution system

the sensors were carefully arranged so that it reduces the spatial interferences. As majority of the sensors are heat sensors and discharges heat it affects the working of the sensor placed near to each other. The figure 4.5 shows the initial circuit implementation that was done in the breadboard with wires. Building the circuit in breadboard gave the flexibility of working with different arrangements. We have tried to expalin the hardware section in our paper [114].

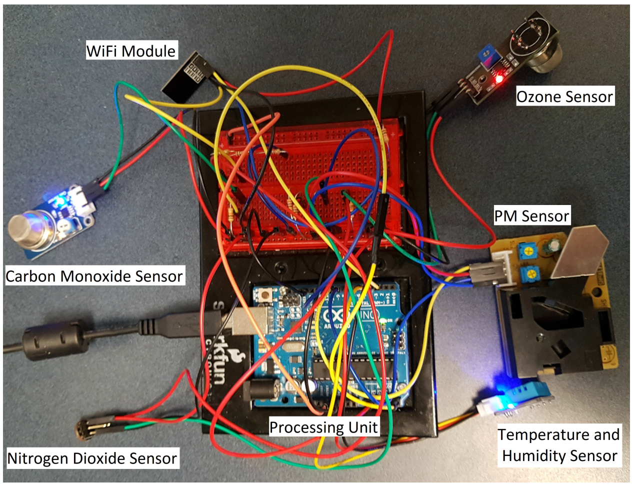


Figure 4.5: Prototype Implementation

After building the circuit in breadboard, it was migrated to a Printed Circuit Board (PCB) developed by Flemings Solution Ltd, India. The design of the board is as shown in the figure 4.6. The PCB was designed in such a way that each sensors and the microcontroller itself was plug-in model to board.

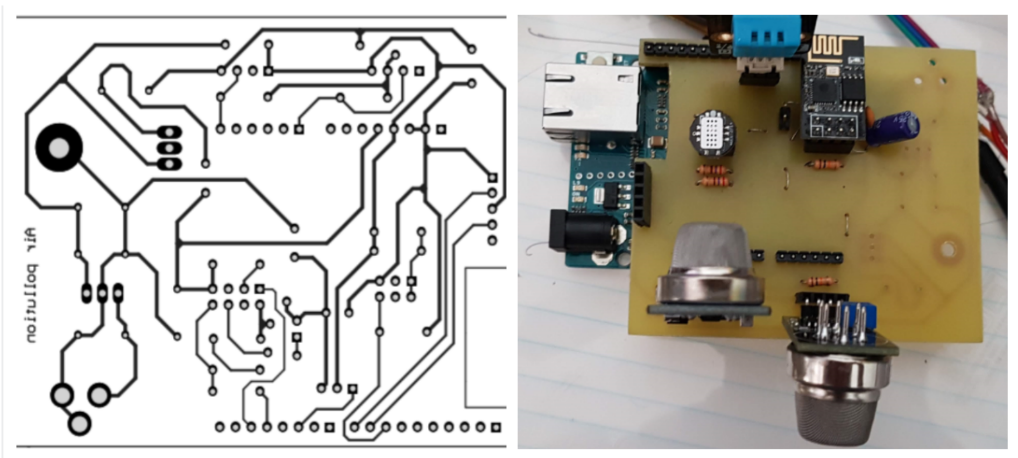


Figure 4.6: Printed Circuit Board

This was done so that in case of any malfunctioning of any of the sensors or processor, it could be replaced easily. The main advantage of using a PCB design is that all the components are fixed and there is no wiring at all. This produces a zero error circuit and there wont be any short circuiting.

4.5 Software Architecture : Customizable Layered Visualization (CLV)

The hardware is the one responsible for the data collection but making these data available to user is done by an effective visualizing software. The main objective kept when developing the system was the data collected should be accessed from anywhere and thats why IoT platforms were selected. We developed a customizable layered visualization of data that potentially involve different stakeholders. We believe an effective visualization of concerned data is critically important for effectively combating major issues such as mentioned above. The software is driven by the following four key elements:

- Stakeholder specific visualization.
- Author-guided and user-driven interactiveness.
- Hierarchical approach to visualization.
- Providing alternate options.

4.5.1 Framework

"Seeing is believing because seeing is seduction" [115].

The pollution monitoring stations collect huge amount of data of pollutants and there are various ways to make people aware about these data. There can be different groups of users who will have access to these data which can be categorized as common people, educationist or the researchers who will be analyzing on the data, and the policy or law makers who will take necessary actions.

Accurately identifying all the stakeholders of air pollution is challenging. In [116], a paper which categorizes stakeholders in environmental risk decisions into four categories of stakeholders as risk losers, risk gainers, risk perpetrators, risk managers. Risk losers in [116] are those who may be adversely affected by environmental risk decision, in terms of health or economic values and risk gainers are those who may be favorably affected by an environmental risk decision, typically through economic gains. The people who create the risk are the perpetrators and those who takes the action against the risk are the risk managers. In a similar way, here we have put forward an approach of visualization based on the different stakeholders, in which we have classified into three categories: risk losers, risk analyzers and risk managers.

Risk losers are those who are prone to pollution which include the common people or the society as a whole. Risk analyzers are those who identify the cause and increase in pollution and suggests pollution control methods. The next category is the one who implements laws and regulation by looking at the trends of pollution for a certain period of time, which are categorized as risk managers. We believe this categorization for representing air pollutant data is very efficent as it helps in representing what each stakeholders wants to see.

The visualization should be very simple and be able to drive the user to which details they have to go through. It should not be representing all the data in a single screen which will be confusing to user and will end up loosing the interest of different stake holders. The user should be able to choose what data they need to view. If this approach is included in visualization, the data that different stakeholders are looking for will be passed onto them in a very efficient manner. We have summed up this visualization idea in the paper that we tried in 2018 [117].

4.5.2 Implementation of CLV of Air Pollution Data

The complete software implementation for visualization was done with the combination of Node.js and python. The framework of the complete software is as shown in the figure 4.7. In the figure 4.7 the back end and the front end of the software is clearly shown and how it is connected with each other.

According to the classification of stakeholders, each groups are looking for different kind

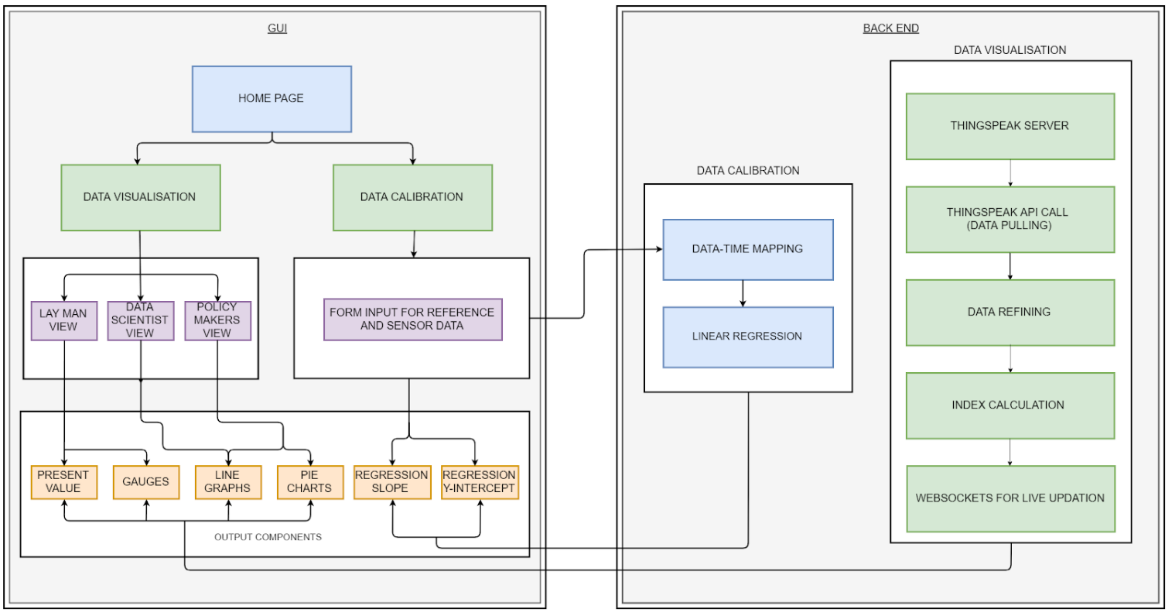


Figure 4.7: Software Architecture

of data. The data can be represented in the form of huge spreadsheets or documents. There are different methods for visualization like heat-maps, bubble plots, box plots, bar graphs or a plane graphs. The most common method of displaying the data is graphical method, which can show the data corresponding to a certain time or day. We believe that instead of visualizing the entire data through graphs or plots, it would be much easier for the public to interpret the data if it is a single instantaneous value. The representation implemented for the first stakeholder which is the layman is as in figure 4.8, which shows a single value of the pollutant which is all the data that as a citizen will be looking for.

The implemented representation is very easy to understand the data and it shows the concentration that each pollutant adds to atmosphere. The idea of this kind of visualization is that the user in the first category that is the common lay men, simply needs to read the data from display. The next implentation is done for the datascientist or researchers in figure 4.9 who need to get a detailed view of the collected data and time. The ideal way to represent detailed information is through a line graphs as it shows the value obtained for a given time.

The value of pollutant could be seen when the pointer is hovered over the graph. These graphs gets updated everytime when the data gets collected at the system as it is important

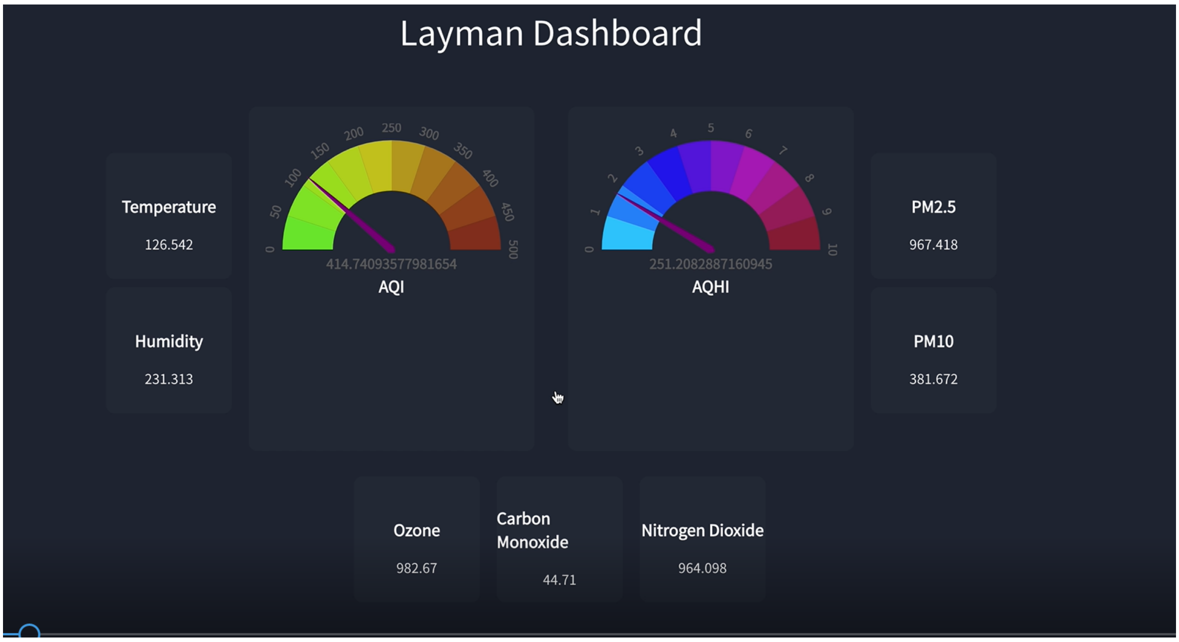


Figure 4.8: Lay man view

Figure 4.9: Data Scientist view

for researchers to go through every collected data. The last categorization of the user is the policy makers who implements action against change in the concentration of pollutant. They are the once who enforce laws by looking at the pollutant data and hence they are the ones who need to see a combined view of all the pollutant as shown in figure 4.10 to understand the trend.

This can be viewed through a pie-chart which shows the percentage of each pollutant that

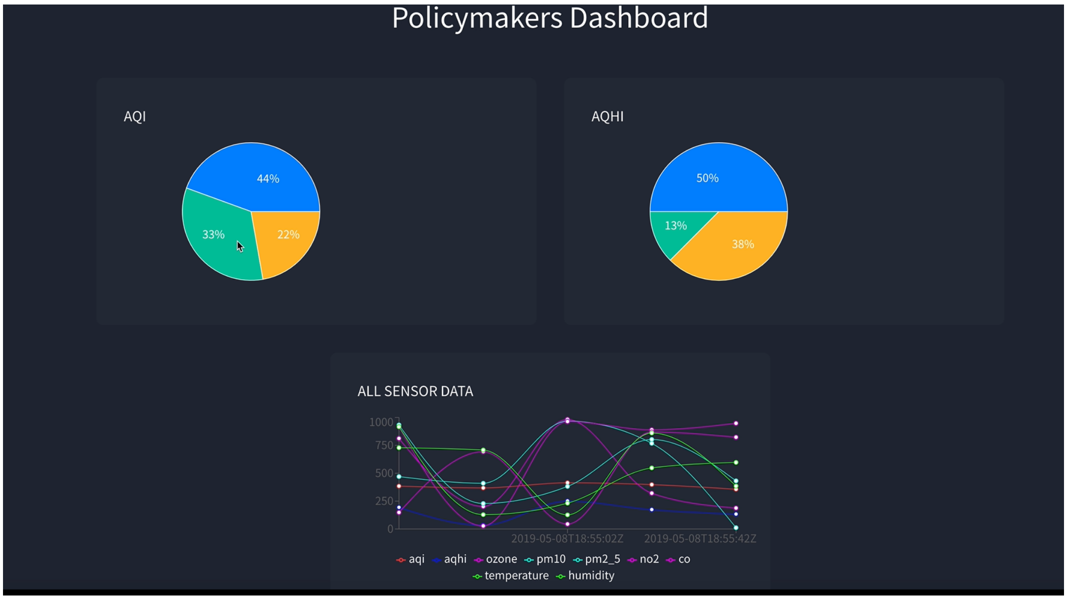


Figure 4.10: Officials view

contributes to the indexes. There is also a combined line graph that shows the concentration of different pollutant data. By looking at the pie-charts and the combined graphs it would be easy to understand the trends and also could find the pollutant which contributes more to the developed indexes.

The idea of such a hierarchial level of visualization is that it changes according to the people who are focusing on these data. Albert Cairo, a renowned information designer claims that the fundamental goal of data visualization should be to make people better informed [115] [118], similarly we also believe that a well communicated data is important for visualization.

4.5.3 Data Storage - ThingSpeak

The previous section demonstrates how the data is visualized. The other main part to be noted that where does the data get stored? The pollutant data that we get from system needs to be stored so that we can retrieve the data whenever needed. For this we use an open source IoT platform called Thingspeak [119]. This is basically a paid visualization service that allows the system to aggregate, analyze, visualize, and store the sensor data

[119]. Thinkspeak can allow many users to integrate their system with other systems for collective and cooperative analysis of sensor data and promote citizen science in solving important global problems. It also offer a 'hub' model for data repository and a set of APIs for accessing and using the sensor data for their analysis and interpretations. We have used data repository service of Thingspeak which is a free service and act as our server. The transferred data from WEMOS is stored into an API key provided by Thinkspeak and updated everytime when the data is available. The data can be downloaded from here in the form of csv file which makes it more easier for analyzation. Having considered all this reason we have used this platform for storing the data.

4.6 Summary

The implementation of hardware and the software along with their architecture have been explored. We have talked about the sensors selected and how it is connected to the Arduino. The different stake holders and how the data is represented for each classification have been discussed thoroughly.

Chapter 5

Experimental Evaluations

The main objective of the study was to compare how close the values from the low cost sensor network is to that of the reference system which is placed at the Plaza 400 building, downtown Prince George. The sensor system was deployed for six days from 30 May,2019 to 4 June, 2019 and was later compared to the values from reference system. In this chapter we will be discussing on the nature of the values and how close are these values to that of the reference system.

5.1 Deployment

In order to understand the accuracy and precison of our system, we deployed the air pollution monitoring system for eight days in University Heights, Prince George in which the first two days the system was put out for calibration and the rest six days for measurement. The figure 5.1 shows the experimental set up of the sensor system deployed at the location. The system was directly connected to a power code and was made to hung over a platform. The collected values were transferred to the ThingSpeak database through the WiFi module (Wemos) in an hourly averaged form and hence 24 data set points were collected for each day.

The main reason to conduct our deployment in this location was to have an easy access and to check on the system regularly in case of any sensor faults or signal distortions. The

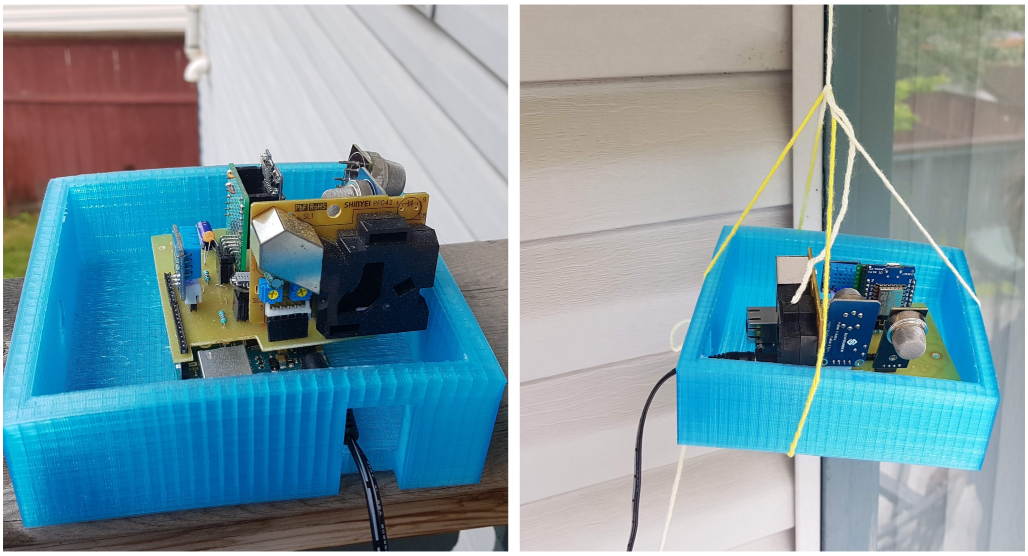


Figure 5.1: Deployed System at University Heights, Prince George

collected values in ThingSpeak database were compared to the reference values located in downtown Plaza 400 building except of carbon monoxide. The reference values for carbon monoxide were not found and hence were not analyzed. We have tried to analyze the daily variation of Ozone, Particulate matter (both $PM_{2.5}$ and PM_{10}), Nitrogendioxide, temperature and humidity to their reference value.

5.2 Calibration

The sensors that we are using to measure the pollutants are low cost sensors and hence the sensitivity of these sensors are less compared to the monitoring station operated by local or state agencies. Inorder to boost the sensitivity of the low cost system and make it equivalent to the values from the monitoring stations we have tried to apply the calibration technique which is linear regression. By applying calibration technique the end result is a calibration curve which is obtained by fitting the most appropriate equation to the set of data [97]. This calibration curve will be as close as to the true value or reference value in our case. We have attempted to calibrate our system by collecting the values for two days and then applying that calibration equation to the system. For each case we have shown the calibration curve as well as the regression fitting curve.

In figure 5.2 shows the graph in which we have plotted three line graphs which includes the reference value from the monitoring station, our sensor value and also the calibration curve. The calibration curve was obtained by applying linear regression and extracting the regression fitting curve. From the line graph it can be clearly seen that the values from our sensor system has low sensitivity and after applying the calibration equation the graph is alligned to that of the reference system.

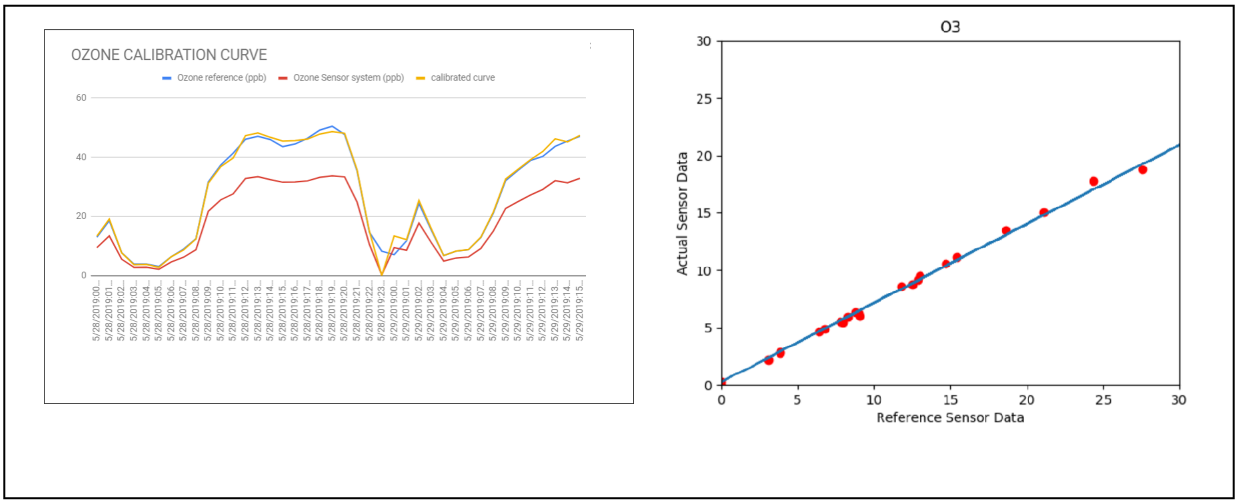


Figure 5.2: Calibration curve and the Regression fitting curve of Ozone

The obtained calibration equation will be in the form of $y = mx + c$ which shows a linear relationship equation. For each of the sensor a calibration equation waws obtained and is shown in the table 5.1.

Pollutant	Regression equation
O_3	$y = 1.45162 * x + (-0.358)$
NO_2	$y = 1.61757 * x + 0.03583$
$PM_{2.5}$	$y = 1.32472 * x + 0.13856$
PM_{10}	$y = 1.62092 * x + (-0.39259)$

Table 5.1: Regression equation for each sensor

5.3 Data Analysis

In this section we will be comparing the collected data for each sensors and will be looking at the accuracy of these values. We will be using multiple line graph plots to observe the data and will be investigating if there is any variations to these data.

5.3.1 Ozone

The ground level ozone which is three atoms of oxygen (O_3) is not emmitted directly from any sources and is termed as a secondary pollutant. Our system measures this with the help of a semiconductor sensor MQ 131 which changes its conductivity with ozone [120].The reference system in downtown uses an API model 400 ozone monitor for the city measurement [121].The figure 5.3 shows the picture of the Ozone sensor used for measurement at the reference station as well as in our low cost sensor system.

Figure 5.3: Ozone sensor used for measurement

From the collected data it can be identified that the content of Ozone gas during the day time is generally high due to the presence of other pollutant and is low during night. It can be seen from the graphs 5.4 and 5.5 that our sensor was able to follow the trend similar to that of the reference system. During the first day of our measurement it can be noted that the value of Ozone from our system ranges for the day one ranges from 13.2 ppb in the early morning at 12:00 am and then the value decreases to 6.32 ppb at 5:00 am. After this the value keeps on increasing to 18.54 ppb at 8:00 am and later reaches its maximum to 55.09 ppb in the noon. From noon till night the value keeps on decresing to 38.47 ppb in the evening to 11.98 during the night. A similar trend is followed for all the days of observation. The maximum value obtained during the six days of observation from our system was 55.09 ppb at 12:00 pm on the first day and the reference system was showing a value of 62.90 ppb which records the maximum .

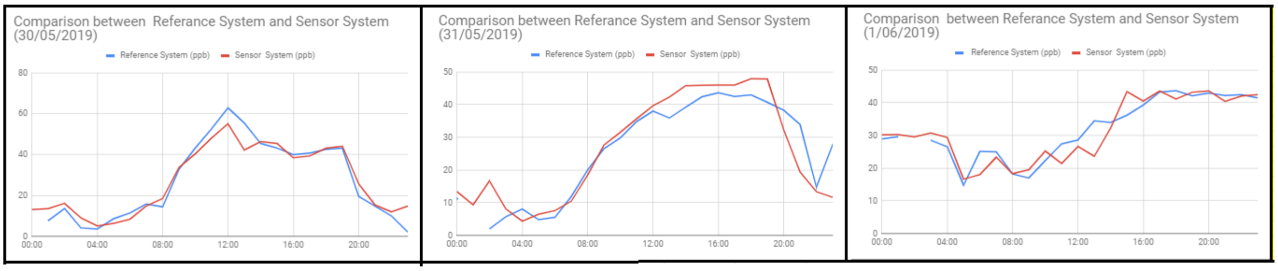


Figure 5.4: Comparison between Ozone values from sensor system and reference system from 30/05/2019 to 01/06/2019

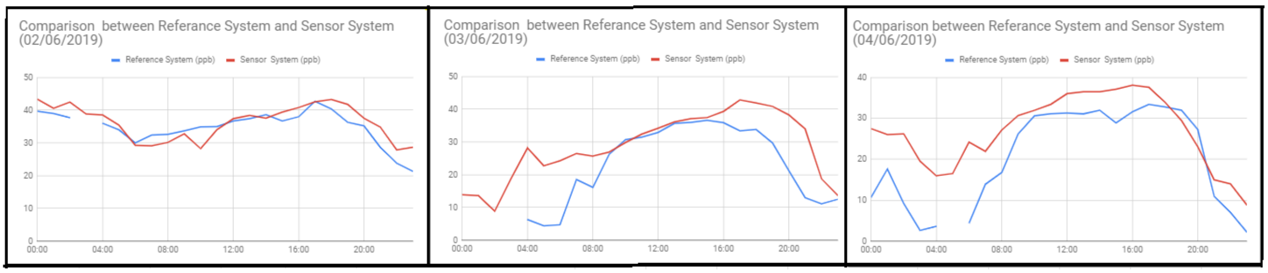


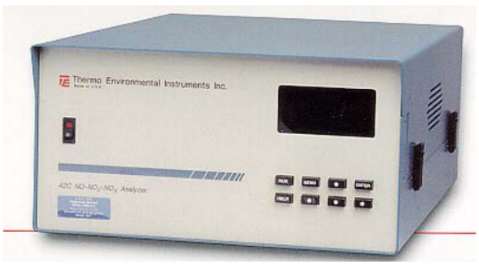
Figure 5.5: Comparison between Ozone values from sensor system and reference system from 02/06/2019 to 04/06/2019

The Graph 5.4 shows the line graphs of the first three days of the experiment and it can be seen that the values are very close to the refernce system. In the next figure 5.5 shows the graphs for the next three days and it can be clearly seen that on the last two days the values from the sensor shows a slight variation when compared to the first three days. This can be interpreted in two ways, either it could be because the system needs to be recalibrated. The system might need to be updated with new regression equation so as to provide the graphs similar to the reference system. Secondly, we can also interpret this as a location specific effect. As the reference system is in downtown and there is a possibility of some activity which can cause a change in values or vice versa. Considering the fact that we are using a low cost sensor to measure the values from the sorrounding and hence the need for calibration should be considered as a priority.

5.3.2 Nitrogen Dioxide

Nitrogen dioxide is found in urban areas which penetrates deep into lungs and causes pulmonary diseases.This gas is generated from liberation of Nitrogen present in the fuels and is considered as a serious pollutant in the environment [27] [122]. We have attempted to measure this pollutant with the help of low cost sensor.

NO_2 was measured with the help of a popular silicon gas sensor called as MICS-2714 by calculating the sensing resistance. The reference system located in Prince George plaza 400 is API NO_x monitor [121] which uses chemiluminesence principle to measure the pollutant . The figure 5.6 shows the image of both the sensors for detecting the pollutant.



API NOx MONITOR

MICS 2714 SENSOR

Figure 5.6: Nitrogen Sensor used for measurement

Using our sensor we have collected values and whave compared it to the values from the reference system. The graphical measurement values of the sensor in comparison with the reference system is shown in the figure 5.7 and 5.8.

The maximum value measured from our sensor system was 25.39 ppb on the first day.

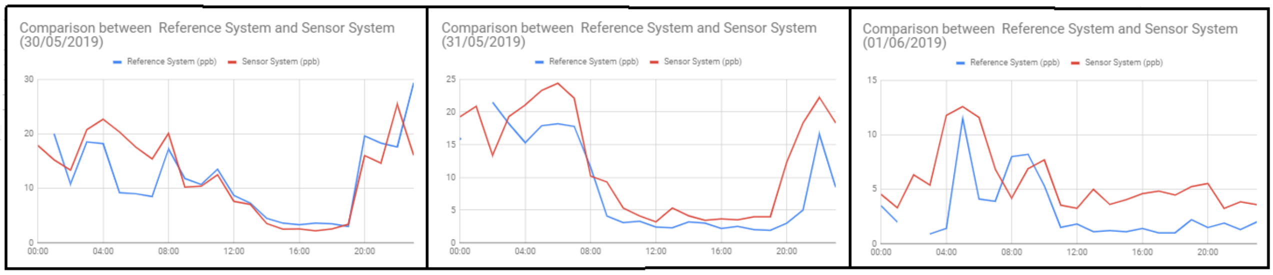


Figure 5.7: Comparison between Nitrogen Dioxide values from sensor system and reference system from 30/05/2019 to 01/06/2019

The values measured from last two days comes under 12 ppb. The values are seen to be fluctualting through out the graphs. It can be interpreted from the graph that even though the values of the pollutant at each point of time is different from the reference system but for the first three days the trend is followed. At the same time it can also be seen in the figure 5.8 that the values from both the system have less similarity.

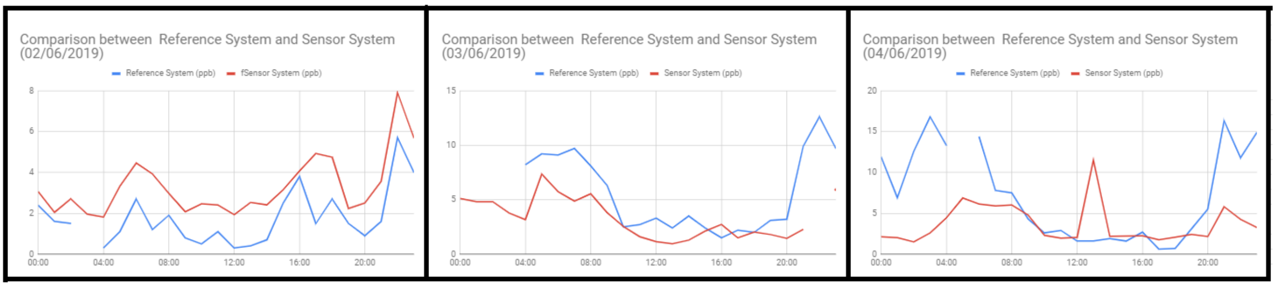


Figure 5.8: Comparison between Nitrogen Dioxide values from sensor system and reference system from 02/06/2019 to 04/06/2019

On the first day our system measures a value of 22.67 ppb at 4:00 am and then the value decreases to around 10.23 ppb by 9:00 am and further decreases to 3.55 ppb at 2:00 pm. The measured value rises to around 16 ppb by 8:00 pm and by 11:00 pm the value is 25.39 ppb. It can be clearly seen from the graphs that the concentration of the Nitrogen oxide are high in the morning and then the slope comes down and again rises in the night. This variation of Nitrogen dioxide can be because of less or no solar radiation in the early morning and late night [121] [123]. The less amount of energy from sun slows down the breakdown of

Nitrogen Oxide to Nitric oxide which inturn increses the amount of Nitrogen oxides in the stratosphere [124] [121]. This can be clearly seen in the graphs in both reference value as well as in our sensor value. Another reason for high values can also be related to heavy traffic as in the graph it clearly shows the concentration hits its peak around 8.00 am which is considered as an office time for most people in the city. The results from our observation shows that our sensor only shows the best measurement for the first two days and later the fluctuation in the concentration is high. This can be due to less sensitivity of the sensor used for measurement or might need better calibration method for the system.

5.3.3 Particulate Matter

The Particulate matters are those particles whose size ranges from 0.001*um* till 100 *um*. The sources for the generation of this pollutant varies from town to town. In Prince George, pulp mills and saw mills are the primary source for their emission and during winter road dust also adds to the primary pollutant category as winter street sanding is done around that time [125]. The activities like street sweeping makes the particulate matter pollution even higher. The studies shows that the PM level are usually low during winter season and are higher during late winter and summer season [124]. In prince george particulate matter pollution is a serious concern and variety of studies are going under this category.

Figure 5.9: Particulate matter sensor

Measurement of Particulate matter was very tricky as there were a lot of options available in market and here we have used an optical sensor named PPD42NS which is a very low cost sensor that calculates the particle size using the principle of infrared. This sensor measures both $PM_{2.5}$ and PM_{10} in an alternative manner. The reference system situated in downtown uses two different method for measurement, continuous and non-continuous [124]. Both the measurement method calculates the pollutant by drawing air from the atmosphere through an inlet and is placed on a teflon coated glass fibre filter [121]. The figure 5.9 shows the pictures of the sensors placed at downtown as well as sensor used for our system is shown.The comparison of both the measurement is done in the following section.

PM_{10} and $PM_{2.5}$

We have plotted the reference data from downtown to the collected data from the system. From the graph shown in the figure 5.10 it can be seen that the values in the morning time especially from 6:00 am to 10:00 am is the highest for every day. On all the observed days the value of measurement did not exceed more than 100 ug/m^3. For the measured value from our system it can be seen that it shows a higher value than the Plaza 400 value. This may be because the building which has the reference system is elevated above the ground and our sensor system are in ground level. This could be the reason why our system shows higher value than the reference system. During the year 1996 a short term experiment was conducted to understand if there is any difference in the street level pollution and was compared to the Plaza site (elevated building). The values collected from street levels shows that the particulate matter values were 30% higher than the Plaza value [121].

Another factor to be taken into account is the location where our sensor is placed and the wind direction. These factors causes variation to the values which makes the graph looks different. Also as the sensor was placed outside a house in uptown there could be activities which happened inside the house such as cooking, vaccuming, smoking etc might have caused these variations. The graph for PM_{10} shows that the during the day time especially

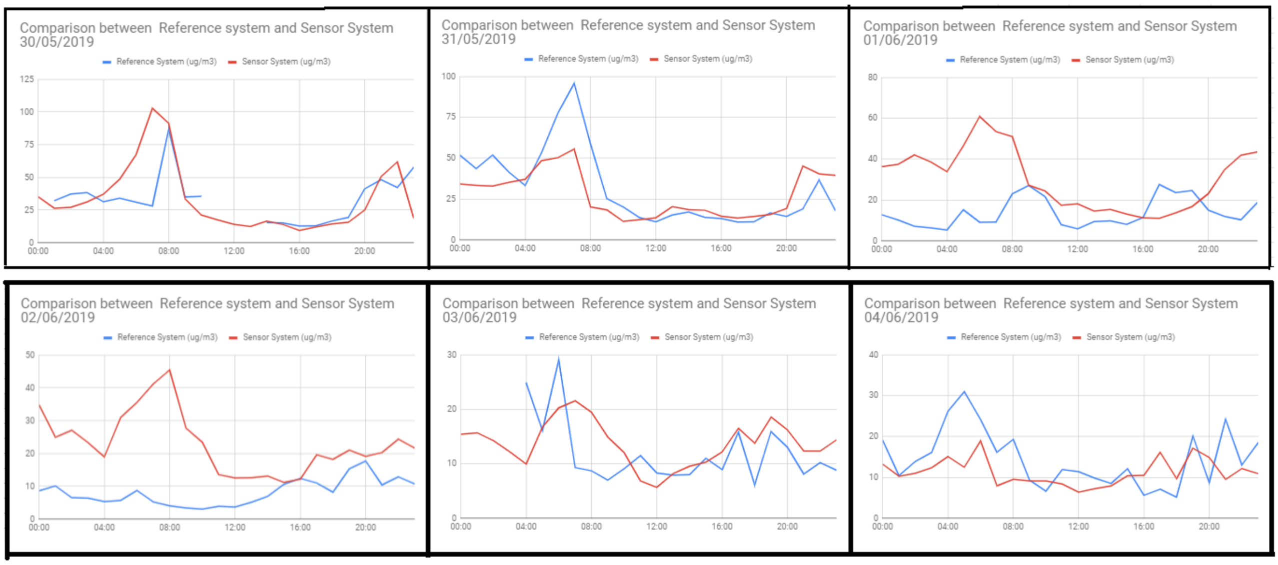


Figure 5.10: Comparison between PM_{10} values from sensor system and reference system from 30/05/2019 to 04/06/2019

from 8:00 am to 4:00 pm on every day the pollutant level is low on the measured day. This is true in the case of the reference value as well.

The factors which contributed to PM_{10} are similar to that for $PM_{2.5}$ like combustion, road dust, industries etc. The particle size of $PM_{2.5}$ are more finer than PM_{10} and has more health effects. On inhaling these particles can causes cardivascular diseases and other breathing problem. From the graph shown in figure 5.11 it can be seen very clearly that on all the measured day the values are low and have not exceeded 40 ug/m^3. The reason for such low values can be also related to meterological factor, wind direction or the location where it is measured. The graphs for $PM_{2.5}$ shows a good similarity to the reference system values.

Unlike PM_{10} the values for $PM_{2.5}$ does not have a regular pattern in the graph. On the first two days the values from the graph showed a higher value in the morning and relatively lower values during the evening and night. On the third day the graph shows some hikes in the value during noon and the evening time. This could be related to some activities that might have occured in the location of the sensor system. On the last three days the pollutant level could be seen as low for the entire day. This is very tricky to identify, unlike other pollutants present in the atmosphere both PM_{10} and $PM_{2.5}$ pollutant level are very

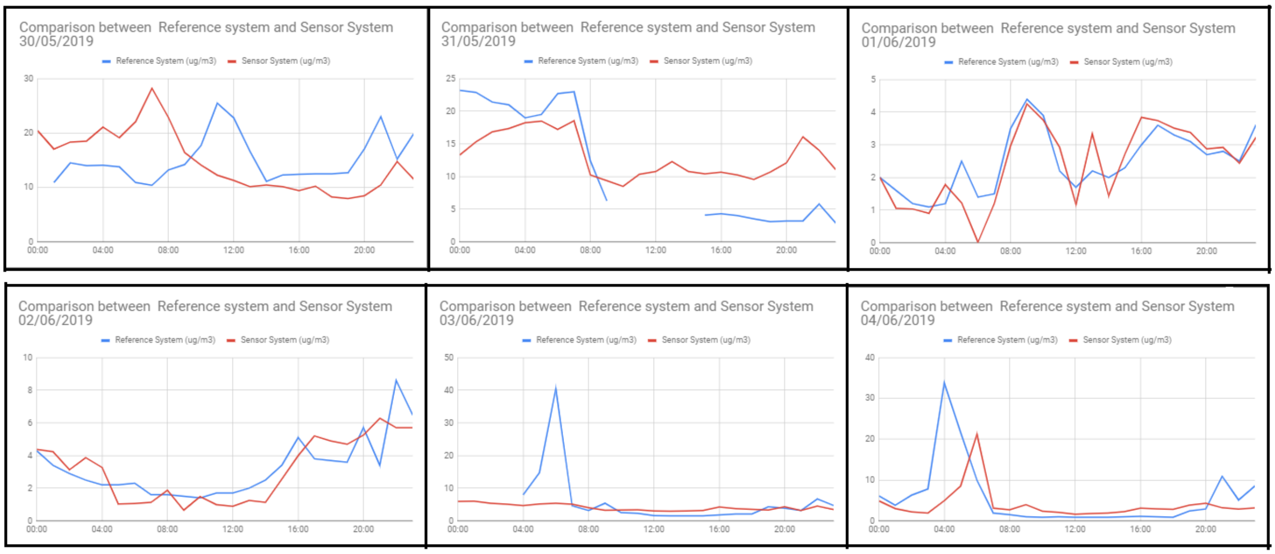


Figure 5.11: Comparison between $PM_{2.5}$ values from sensor system and reference system from 30/05/2019 to 01/06/2019

dependent on location and any small activities could make the values go high or low.

5.3.4 Indexes

The indexes are the numbers which makes the general public understand more about the air quality in the area they live in. In our analysis we have attempted to compare the AQI (Air Quality Index) and AQHI (Air Quality Health Index) indexes from the collected values of both the system.

In Canada the most popular index for the public is AQHI is a number scale which defines how the air quality affects the human health [126]. The pollutants which are included for the calculation of the health index are NO_2, $PM_{2.5}$ and O_3. In our graph we have calculated the health index for each hour and then we took the average for the day and have compared it with the averaged health index data provided by the government. The value of AQHI ranges from 1 to 10+ (highest). The figure 5.12 shows the bar graph which compares both the values.

The first day both the average AQHI from the reference system and the sensor system gives almost equal value which are 3.12 and 3.11 respectievely. On the next three days our

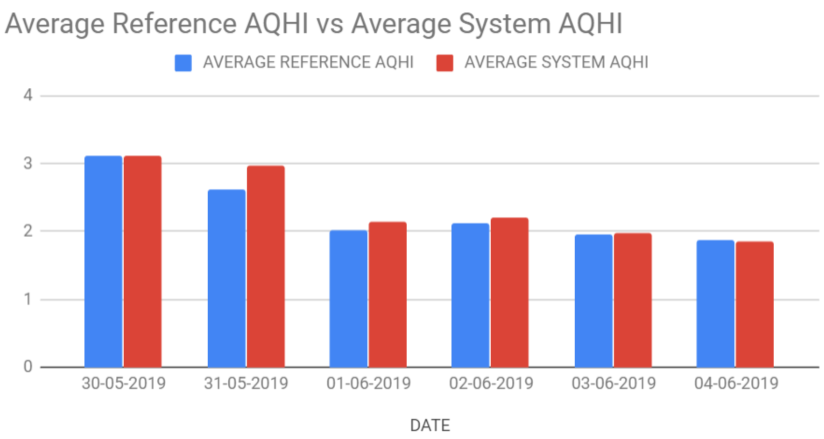


Figure 5.12: Comparison between average AQHI from both Reference and Sensor System

system showed a higher AQHI value than the reference system and on the last two days the averaged AQHI value is same as that to the average reference system. This change in value is because of the variation in readings of the measured pollutant discussed above. On all the measured days the risk factor associated with health is low as per the index chart provided by the government [126].

The next index that we calculated is AQI in which we have used the same set of pollutant that we have used for the computations of AQHI. This index shows how polluted the vicinity is by giving the public a value between 0 to 400+ (highest). Here we have again used the average value for both the measuring system. The figure 5.13 shows the graph of the averaged AQI values.

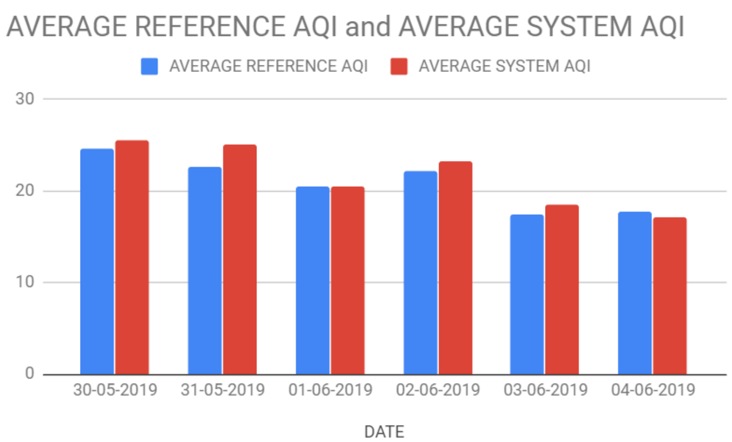


Figure 5.13: Comparison between average AQI from both Reference and Sensor System

It can be seen that on majority of the days our sensor system shows a higher AQI value when compared to the reference system except on the last day. This can again be related to the alteration in the observed value from the reference. These averaged values falls into the first category of the scale provided by the government which means the air quality during the measured days was 'Good'. For the calculation of AQI we have not included Carbon monoxide and PM_{10} as well. Having a look at both the graphs it shows how well the system could capture the values after calibration.

These are the observation which we have obtained after we have put our system out for six days. The system worked very close to the reference system after the calibration except for Particulate matter. Further in the next chapter, I will be proposing on few suggestions which could be done to the system.

Chapter 6

Conclusion and Future work

The advancement in sensor technologies have given a lot of opportunities for researchers to explore in different fields. These technical advancement have opened the door for solving major issues and one of them is environmental issues like air pollution. Air pollution have been a major concern ever since industrialization and modernisation has hit the world and from then onwards it went on increasing. There has been immense number of research works been done in this area.

In this work, I have attempted to put my knowledge of electronics to build a sensor system which measures the pollutants specific to Prince George. The system which I have tried to build is very simple , easily replicable and all the sensors used are low cost and readily available. Then I have also put my hands on the visualization of the collected data and calibration. For visualization we have created an IoT platform in which the data was represented for three category of people. The system was deployed and the data was observed and it could be seen that the data after calibration are close to the reference system. From the graphs it can be seen that the values obtained from the system showes a better correlation with the reference data. One of the major drawback with these low cost system is that they are highly vulnerable to damage by external factors like rain. Another drawback is that the system needs constant recalibration in order to provide accurate data.

6.1 Future Works

There are many ways this work could go forward and some of them I have listed below:

1. The system could be elaborated with different set of pollutants. In the present system we have only used a certain set of pollutant but there is a possibility to expand the system by adding another pollutant like TRS (Total Reduced Sulphur) or SO_2
2. The visualization code can be extended and added different features to it. The software could be made more user friendly.
3. In this work the calibration equations are put into the system manually. This can be coded and automated so there will be less effort for the user to have it recalibrated.

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