Chapter 1

Introduction

Earth, our home planet, is the only known place in the universe that is affirmed to host life [1]. The life on earth is characterized by three components, air, land, and water. Each element has its own special property and is required in its proper proportions to maintain the healthy life of all living beings [1]. However, industrial development and other manmade activities creates a disturbance in the natural environment. The process of making environment unsuitable and unsafe for the living by introducing substances that are harmful to the sorroundings is called pollution [2].

Pollution changes the quality of the environment and is transboundary, as they travel thousands of miles [1]. The introduction of harmful solid, liquid or gasious substances from human activities into the environment changes the quality of the sorrounding that we live in [2]. The presence of pollutants in the environment make adverse impact on human health and sorrounding [3] [4]. Many types of pollutants contribute to global warming and climate change which are the major issues tackled by environmental scientist these days. Out of different types of pollution, antropagenic air pollution plays a major role in climate change as well as international public health issue [2].

Air contamination alludes to release of pollutants into the environment that is unfavorable to human wellbeing and the planet in general. Air pollution is stated as a complex mixture of gases and particles whose sources and composition vary over space and time [5]. The boom in the development of industries and technology have created an alarming situation that is, degrading the quality of air. Contamination of air is a matter of serious concern and society is unaware of the impact that it causes to human health as well as to the surrounding.

The World Health Organization (WHO) reported that death rate estimates are around 7 million every year as 9 out of 10 people breathe polluted air [6] [7]. This has made many motivated individuals like researchers and communities to work towards creating awareness among the people. Various studies are underway on air pollution due to its increasing effect on the environment day by day.

This brings to the reason on choosing my research topic as I always wanted to work towards a social concern. Having the background in electronics and combining with advanced computer skills seems to be a perfect combination for problem solving. In the following section, I will discuss the background to introduce my research work.

1.1 Air Pollutants and Measurement Metrics

There are various pollutants that contribute to the contamination of the environment. These pollutants differ from region to region depending on the human activities. For example, in an industrial area which manufactures products from raw material, such as production of iron from its ore or production of gasoline from crude oil, releases inorganic carbon compounds into the atmosphere [8]. Urban areas are the major sources of particulate matter and carbon compounds produced from the burning of fuels in the vehicle.

Based on the severity of health impact and the kind of human activities, the United States Environmental Protection Agency (EPA) established the National Ambient Air Quality Standards (NAAQS) under the Clean Air Act which specifies the pollutants that are harmful for the public health and environment [9] [10].The National Ambient Air Quality Standards (NAAQS) has set six common criteria pollutants that harm human health, environment or even property damage. The pollutants specified by NAAQS are Particulate Matters (PM), Ozone (O_3), Nitrogen Dioxide (NO_2), Carbon Monoxide (CO), Sulphur Dioxide (SO_2), and

Lead (Pb).

Different countries measure different set of pollutants, for example, India measures eight major pollutants such as (PM), (O_3), (NO_2), (CO), (SO_2), Ammonia (NH_3), and Benzene (C_6H_6) (in some places (Pb) instead) [11]. Most other countries measures a subset of these criteria pollutants, for example, Canada measures PM, O_3, NO_2, SO_2 and CO [11].

Particulate matters are the particles that are formed in the atmosphere due to a chemical reaction between different pollutants in the environment [2]. These particles vary in their diameters and is measured at two levels; fine partcles which are 2.5 microns size particles ($PM_{2.5}$) and coarse particles which are 10 microns size particles (PM_{10}), and they are measured in micro-grams per cubic meters ($\mu g/m^3$) [12]. Carbon Monoxide (CO) is produced from incomplete combustion of fossil fuels such as motorvehicle emission [13]. Majority of the CO present in the atmosphere are from road traffics and rest are from burning of other fuels [13]. Another vehicle emitted gas which causes adverse impact on our sorrounding is Nitrogen Dioxide (NO_2). This gas can causes adverse pulmonary disease when inhaled in high concentration [14]. Next serious pollutant present is Ground level Ozone (O_3) which is formed from a chemical reaction between pollutants which are emitted from the man made activities like oxides of Nitrogen or Volatile Organic Compounds (VOCs) with sunlight [15].

Each country identified there set of pollutants and measurement unit for these pollutants.The most popular units used to measure these pollutants are either in parts per million (ppm) or in parts per billion (ppb). For a layman to understand these individual measurements and its cumalative impact on the quality of air is challenging. Taking this into account the government agencies of each country around the globe developed their own indices corresponding to the NAAQS for representing the quality of air. The different indices are 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. Out of all these indexes the most common are AQI and AQHI which are proposed and used by different countries [11].

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 environment. AQI is a piecewise linear function of the pollutant concentration [16] and is measured using the following formula.

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

where I_i is an air quality subindex 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 the Figure 1.1 and each colour code shows the quality of air in the atmosphere.

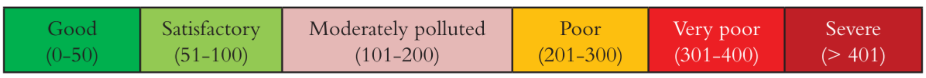

Figure 1.1: Air Quality Index (AQI) [17]

In Canada, the Environmental agency developed AQHI to make the common public aware about the quality of air that surrounds them and how it effects their health. 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 very less in predicting health effects. The following formula computes 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, $B = 0.000871\times$ concentration of NO_2 and

$C = 0.000487\times$ concentration of $PM_{2.5}$. The value of AQHI varies from 1 to 10+ as shown in Figure 1.2

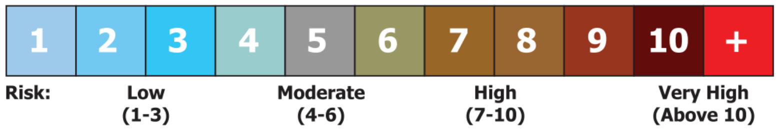

Figure 1.2: Air Quality Health Index (AQHI) [18]

Now the question is which is a better measure, AQI or AQHI? Health index was created with a different objective in mind that is to provide the effect of pollutants to the human health. AQI is based on a single pollutant and hence it is hard to see its direct relationship with health [11]. On the other hand AQHI is based on the exposure-response relationship between the major air pollutant mix and human health [11].

1.2 Impact of Air Pollution

Air pollution has significantly increased after industrialization and urbanization have taken place. The burning of fossil fuels, exhaust from factories and industries, and mining operations are major contributors towards air pollution. Exposure to air pollutants causes premature deaths, cardiovascular disease, stroke, and other respiratory diseases. The state of global air 2017 has discussed the effects of long-term exposure to harmful air pollutants such as particulate matter which contributes to over 4 million premature deaths and is estimated to double by 2050, if the issue remains unattended [5]. Air pollution accounts for highest death rates annually.

Fine particles ($PM_{2.5}$) and coarse particles (PM_{10}) causes the greatest threat to health, as they are capable of penetrating the lungs which leads to cardiovascular and Chronic Obstructive Pulmonary Diseases (COPD) [6] [19]. Exposure to Carbon Monoxide (CO) which is a colorless and odorless gas, results in absorption of the gas into bloodstream and reduces the ability of lungs to transfer oxygen which inturn affects the functionality of vital organs such as brain and the heart [20] [21]. Respiratory issues such as decrease in responsiveness of airways, inflammation in airways and lung infectivity occurs due to exposure of high concentration of ozone (O_3) [22]. Another pollutant is nitrogen dioxide (NO_2) which causes illness such as wheezing, coughing, bronchitis and increases severity of flu symptoms.

The exposure of mixed air pollutants leads to health effects like birth defects, development delays in children, skin irritation or even cancer [23]. Apart from the health issues, there is a large effect in environment such as rise in sea-level, global planetary warming that contributes to increase in overall temperature and melting of ice caps, acid rains which leads to land and crop destruction, ozone layer depletion, wildlife destruction and eutrophication which affects on aquatic life [24]. Having discussed the effect of pollution the next section will brief about the history of air pollution and how pollution is measured.

1.3 Background

The sucess of industrial revolution was only there for technology, economy and society.At the same time there was a large amount of pollutants being released into the environment creating a mismatch in the proportion throughout the world [2].The quality of the air has declined since the industrialization has taken place in the mid 19th century.

Ever since then it has affected not just the environment but also human health. Development of heavy industries across Europe and North America used coal as their major source of energy which contributed to black smoke pollution [25] [26]. Coal was not just used in industries but also in houses for heating in winter which made the pollution even worse [27]. These emissions resulted in serious health impacts on residents in urban areas that increased the mortality rate during 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 [28]. There was a string of similar events reported in New York and England around the same time. All these incidents led to the development of Environmental Protection Agency (EPA) who enforced the need for installing the monitoring stations. The government along with these environmental agencies established acts like clean air act, motor vehicle air pollution act, air pollution control acts for a better quality of air [29]. Apart from that, they took initiative to monitor the air pollution by installing systems which could measure the concentration of pollutants and could give warnings to public as well as industries regarding how polluted the atmosphere is.

1.3.1 Existing Environmental Monitoring station

The government and environmental agencies are making an effort to install monitoring stations for improving the air quality. The EPA monitors the criteria 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 not just monitoring criteria pollutants but also analyzes 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 [30] [31]. These sampling techniques are considered as one of the most significant development for air quality measurement and used widely for monitoring purposes.

In passive sampling the pollutants are collected by physical process such as diffusion through a static air layer or membrane. These pollutants in the air are diffused to adsorb on the sampling media due to difference in the chemical composition of pollutants. The analysis of the pollutant on the sampling media gives the time-averaged contaminant concentration [32]. On the other hand, active sampling works with an air sampling pump which actively pulls the air through a collection device like filter and weighted concentration is calculated. However these static instruments have a major drawback of temporal resolution as they are large in size and needs high maintenance. These instruments are expensive and are financially impractical to expand to more than one station. Table 1.1 gives the average estimated cost for purchasing air quality monitoring equipment produced by US Environment Protection Agency (EPA).

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

*FTIR: Fourier Transform Infrared spectroscopy measures multiple gases

Table 1.1: Estimated cost of Reference Instruments [33]

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

1.3.2 Portable Sensor Network and Air Quality Monitoring

There is an emerging trend of using air sensors to understand the quality of air because of its low cost, small size and low power consumption [34]. These sensors are cheaper than reference station and can be replaced easily in case of any damage. The advancement in the Micro-Electro-Mechanical System (MEMS) made it possible to integrate all the functions into a single electronic circuit which makes it more compact. These sensors do not incur deployment cost, infrastructure cost or does not require frequent maintenance which makes the overall expense even less.

Sensors are used in variety of application such as military monitoring purpose, surveillance and tracking, traffic density calculation and road condition and environmental applications [35]. Sensor units can be accommodated on an automobile, building tops or even could be in a wearable form in order to track or measure. This enables high spatial resolution without establishing huge reference station [36]. Sensors measuring different compounds are integrated together to make a sensor node system. Extensive research works have been done with the available sensors in the market.

1.3.3 Pollution Monitoring System in Prince George

The human activities within the physical environment has been taken into account and these activities influences the environment that we live [2]. 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 an area can highly affect the quality of air. Another factors include topography, atmospheric conditon and magnitude of emission sources [37]. Having considered all these factors over the years in Prince George the government agencies along with industrial partners funded for the installation of fixed monitoring station for the measurement of the dominant pollutants in the area [38].The map below shows the layout of the monitoring stations which was released in the air quality report of 2016 [39].

Figure 1.3: Map representing the Fixed Monitoring Station in Prince George [39]

Out of the eight monitoring stations installed, there is a core station that measures all the six pollutants which includes $PM_{2.5}$, PM_{10}, TRS, SO_2, NO_2, O_3 and the rest only measures certain pollutants or meterological data [39]. Plaza 400 monitoring station is located in downtown and here the air quality can be recognized as a combination of industrial, commercial and residential emissions [38]. There are several instruments like SHARP model 5030, TEOM 1400a analyzers and TRS samplers used for collecting the environmental data [39] [38]. These data are available in the Ministry Of Environment (MOE) [40] website and the data from these websites can be accessed and downlaoded by public.

1.4 Motivation

One of the important components in solving the issue of air pollution is to increase the awareness among public about the current situation and its impact so that they can act on it. The conventional method of monitoring the air quality with the help of a few heavyweight expensive stationary monitoring systems typically installed by the state may not be effective enough for this task. To achieve the goal effectively and without further delay, 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 global system. With the technological advancement of low-cost computing, communication, and sensing devices, and the revolution of open source software [41], we believe it is possible to build pervasive air pollution monitoring system with the available sensors from the market and building an open source software. Now the question is how to design such pollution monitoring devices 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 an open source tool for representing the collected data from sensor. Some recent attempts to build a low cost air pollution monitoring system have been done, however, none of them are simple and easily re-producable. 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 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 many amateur electronic hobbyists to buy the hardware locally and download the associated software to build their own pollution monitoring device.

1.5 Research Problem

This thesis focuses on design and development of an air pollution monitoring system using off-the-shelf hardware and build an open source software that focuses on three different types of users with the following objectives in mind:

1. To demonstrate the quality of data obtained from the low cost system by comparing it with the expensive monitors fixed at a particular location.

2. To encourage citizen to contribute in solving the issue of air pollution and to give more insight about the impact it causes to human health and environment.

3. To give an idea on how to integrate the hardware components to a processor and also make an independent software, which can be accessed world-wide.

4. To provide user oriented data which gives a deeper understanding about the pollution.

5. To provide information on the quality of air by including Air Quality Health Index (AQHI) which provides a measure of adverse affects on health by pollutants and Air Quality Index (AQI) that gives an idea about the level of pollution on the environment.

6. Improving the quality of data obtained from the system by integrating a calibration tool.

1.6 Thesis Contribution (WILL BE REVISING AGAIN AFTER WRITING RESULTS)

There are three major contribution from thesis:

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

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

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

1.7 Research Question

Some important research questions to be addressed related to the issue of air quality are:

1. What kind pollutants affect the human health most? How to measure them?

2. As the pollution is in the atmosphere, should it not be measured everywhere all the time? If so, what kind of infrastructure is needed to facilitate such a ubiquitous measurement?

3. What all factors should be considered while selecting sensors for measurement of pollutants?

4. Which processor to be used for processing the data collected from sensors?

5. How should the hardware component i.e the sensors and the processor, should be packaged?

6. What is the difference between different metrics which is used to show the effect of pollution?

7. How can the seriousness of pollution be made aware?

8. How can the representation of Air quality metrics be done?

1.8 Research Challenges (WILL BE REVISING AGAIN AFTER WRITING RESULTS)

The major challenges experienced on creating a complete system are:

1. The integration of different sensors with the processor.

   As each sensor has its own property, there can be issues when connecting all of them together in a single platform. Most of the sensors used for measurement are heat sensor and needs to be powered atleast 12 hours before operating. There is a particular operating temperature range for each sensor connected. As each of the sensor needs different environment for working, all the factors should be incorporated for a complete working environment.

2. Calibration of each sensors based on the data sheet.

   As I am selecting low cost sensors which comes with calibration with respect to the environment it was developed. The collected data changes for each environment and this should be taken care of. This can be a tough task as for each of the sensors it changes based on the slope of internal resistance and the internal voltage values given in data sheet.

3. Packaging of hardware component.

   To make the whole system portable it should be packed carefully. For certain sensor like dust sensor, it should be exposed to the environment so as to estimate the particulate matter. This packing should be done in such a way that the it does not hinder with the observed value.

4. Development of the visualization software.

   The development of user specific visualization tool from the scratch was most challenging as this was my first hands on experience in creating a tool which involved different methods of data display. Another task was to make the tool connect to the backend python code which does the data clensing and calibration which took a lot of preparation work.

5. Transferring the data to a platform or a database using the WiFi module.

6. Checking whether the collected data is accurate.

1.9 Structure of the Thesis

Rest of the thesis is organized as follows. Chapter 2 focuses on 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 Chapeter 3 the design and implementation of pollution monitoring system and the visualization tool is explained. To test the accuracy of collected data to the orginal data we have implemented calibration tool by linear regression which is described in Chpater 4. In Chapter 5, analysis of the results obtained from the system is demonstrated. Finally, in Chapter 6 the conclusion and direction for future work are provided.

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 more in various field of science such as health care, military applications, traffic control, monitoring and data collection [42] [43]. 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 the society today. There are different approaches for understanding air quality and this chapter gives an overview on the research work done in academic literature that is classified based on different platform used for the measurement [44] [45].

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

The research done in different platform will be explained in detail further in this chapter.

2.1 Vehicle based sensor network (VSN)

In recent times, the number of private vehicles on the road have increased in proportion to the increasing population [46]. Even though the increase in automobile is one of the major factor that is contributing to the increase in pollution, certain researchers took this as a medium for collecting air pollution data. In this category of work, the vehicles (like buses or cars) are installed with a portable, low cost sensor so as to obtain spatially resolved data.

One of the best way 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. In order to solve this issue, in 2009 a group of researchers used mobility as a method and proposed a Vehicular wireless sensor network [47] 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 Carbon Dioxide (CO_2) sensor, Global System for Mobile (GSM) module, GPS receiver and an intra-vehicular network by ZigBee module. The collected data is transferred through GSM short messages to the server and is displayed on google maps for results. This work faced two network related drawback firstly there was duplication of air pollution data as the number of vehicles is a given area changed dramatically from time to time and secondly the data transfer depends on cellular network which incurred charges. These two problems were later addressed in 2011 in [48] by designing two algorithms. They also created a simulation model to verify the performance of algorithm. The above two research work mainly focused on data collection, optimization of the collected data and was only centered around one pollutant. The problems like calibration of sensors, visualization of data, checking the accuracy of the collected data and management of the VSN was not taken care of.

Volgyesi et al. [49] in support with Microsoft proposed Mobile Air Quality Monitoring Network (MAQUMON) that measured three pollutants, Ozone (O_3), Carbon Monoxide

(CO), and Nitrogen Dioxide (NO_2) in contrast to one pollutant in [48]. The air pollution system is mounted on a car and is powered by a Li-ion battery whose battery life is limited for 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 web server and visualized in sensor map web application in the form of contour maps. However, inability of representing instantaneous data is one of the main concern with this system and also have failed to show the accuracy of collected data to the local system.

Another attempt for collecting fine-grained pollutant data is demonstrated in [50]. In order to increase the spatial density it proposed two data framing models one for a public transportation infrastructure and other for a personal sensing device. In public transportation a Mobile Sensing Box (MSB) was installed in 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 bus batteries and the collected data were transferred to server and visualized using google fusion tables interfaces. In the second framing, Personal Sensing Device (PSD) that included a air quality sensor which was installed in cars and connected over a bluetooth to a smartphone. This gave the user aware 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 result showed a positive linear relationship between the two data. Eventhough there was a high correlation seen between the two sets of data points there was again no comparison with the local data to understand the accuracy of the system.

A similar technique of data collection like in [50] can be seen in wireless sensor deployment [51] that proposed the idea of placing the sensor nodes in public transport buses in order 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 environment and latter aggregates the data from the sensor node and transmits to a server via a long range radio bands. 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 regular interval of time and can be analyzed instantly. However, the paper did not discuss about the collection of data and failed to provide the quality of collected data.

A research group from Japan, Shirai et.al [52] proposed an effective method to acquire air quality data in urban area in which the air pollution system has a sensing unit kept on a public vehicle like garbage truck and grabage 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 [50] which by the 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 which was taken for understanding the air quality was public bicycle system. The bicycle borne sensor [53, 54] deploys a system equipped with 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 micro storage chip. The system is powered with the help of Lithium polymer batteries. When the subscriber returns the bicycle to dock station the data is transferred to data centre via bluetooth module and is then visualized using 'baidu' heat map.

In [55], Unmanned Aerial Vehicle (UAV) is used as a medium to understand air quality. In contrast to the work done in [47–54] 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 smart phone is attached that collects data from 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 shows 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, 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 about the quality through the indexes. The efforts to calculate AQI or AQHI is not taken as a priority except in [55]. The representation of these indexes will make people aware about the air quality but most of the work in this category have 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 [56] this will give an idea about the amount of pollutant inhaled by an individual. This could be achieved by using wearable sensor which helps to understand the effects of individual impact when exposed to polluted air. Research done in this section mainly focuses on improving the understanding of the personal health and exposure to air pollution [57]. One such development is Mypart [19] from the University of California, is a wrist worn particle sensor that measures particulate matter of 10 microns or less. The design of MyPart is based on traditional laser based photo diode 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 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' [58] 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 web server which was developed on a simple java script application. The next wearable work is 'citisense' [59] 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 back end to a web server where the user can get a personalized view of their data. They also developed a citisense android application that runs on the smartphone.

In [60], the research group in 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 [61] developed a novel system consisting of several sensors that gives a real-time feedback of an individuals 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 calculates the inhaled dose of pollutant by calculating the volume of air inhaled into a person's lung per minute through an algorithm developed in [62]. The inhaled dose of pollutant was calculated and compared during various activities like jogging, bicycling and driving.

There are also wearable sensor projects initiated in Vancover in association with University of British Columbia like TZOA [63] that can be clipped to the clothing and measures the air quality. It mainly measures PM values and display in an application. These devices decreases the gap between individual and their understanding about the polluted air. In NewYork a striking project named 'Aircasting' [64] which provides the health and environment data using android 'Aircasting app'. The 'Aircasting' [65] platform includes a palm-sized air quality monitor which measures $PM_{2.5}$, relative humidity and temperature. The outside air is drawn through a sensing chamber and the particles are measured through light scattering method. It also includes a LED wearable apparel named 'Air casting luminisence' [66] that illuminate LEDS according to the obtained sesnor measurement; variying from red for high intensity, then orange, then yellow and finally green for low intensity.

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

2.3 Community sensor sensor

The development of portable sensor devices have 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 webinterface. The collected data from the participants gives a spatiotemporal view of the effect of pollution [67]. In Sydney a low cost participatory system is deployed named 'Haze-watch' [68] for monitoring pollution in urban areas. In this, mobile sensor units was 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 send to a cloud-based server which stores data and applies interpolation models [69] 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' [70] which is based on mobile participatory sensing [71] that enables citizens to collect relevant data and involves in the decison 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 muncipal fleet of street sweepers in the city of San Francisco [72]. Another community-driven sensing developed is 'OpenSense' [73] which focuses towards the utility of data by giving an idea about how the data collected from sensors needs to 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 Swizerland and the collected data is pipelined to a Global Sensor Network (GSN) from where the streamed data is processed and represented. In [74] an outdoor participatory monitor was introduced called 'GasMobile' by connecting low-cost ozone sensor to an android smartphone. The collected data from the sensor is transfered to the phone and from which it is visualized using application as well as 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 opening for a further participatory sensing research in Swizerland supported by samsung called 'Exposuresense' [75] that monitors user activities like walking, running, etc., from smartphones and understanding their exposure from obtaining datas 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 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' [76], for Gloabl-Sense, is a work initated 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 environment data, and Human-Centric Sensing (HCS) for heath related datas for specific group of users. The sensors collects the data and sents 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' [77] 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 official, doctors, and community developers with data so as to get a deeper understanding. They have also pointed out the research oriented challenges that needs to be addressed when building a community networked system like security, privacy, data visualization and working towards to achieve 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 [44] are a few challenges researchers are trying to work towards it. The cost of maintenance in such 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 [45] 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 are complex, bulky and expensive; hence there is a need to develop portable and low cost environmental monitoring system. There are various noticeable research work done under this category and I have briefed relevant ones.

The Integrated Environmental Monitoring System (IEMS) [78], 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 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 web server that provides a 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) [79] that designed a data regression algorithm named Recursive Converging Quartiles (RCQ) to remove duplicate data and then calculate AQI values. The array of sensor node collects the pollutant data and transfers it to cluster heads where the RCQ is applied to improve the efficiency and alleviate congestion problem. From the cluster head the data is send to server and represented using line graphs for each areas.

'AirSense' [80] is an excellent approach to asses the 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 which 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 work on 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 behavior so as to provide intelligence to the system. The system has also got a smart phone application which gives the users a very effective interface for visualizations and understanding the data. In [43] a different group of researchers from China developed the system 'Air-Sense' to monitor and predict the quality of air based on ZigBee network. The system uses 4 different type of sensor, respectievly are humidity, temperature, $PM_{2.5}$, Total Volatile Organic Compund (TVOC includes the general organic gases) and a ZigBee transreciever 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 standard value predicted by WHO.

Another static work which focuses on indoor air quality is demonstarted in [81] in which the main focus is to understand the pollution in office environment where the pollution is triggered from the electronic devices and machines. In this the primary pollutant measured is ozone which is mainly emmited from a photocopier machines. The system is designed into different nodes where the sensing node contains the Arduino which process 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 formated as IP packets and forwarded over the Ethernet network to processing node. The data is saved in database and using 2D graph the concentration gets visualized. A research group from Harvard university developed a wireless networking testbed called as 'CitySense' [82] in which multiple environmnetal sensors are attached to street lights. These sensors were deployed in Cambridge and data was uploaded to server using mesh networking like RoofNet [83], TFA [84] and CUWin [85]. 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 [86] developed a micro-scaled air quality monitoring system for understanding the CO emmision from vehicles by integrating the sensor nodes with a gateway. The data collected from sensor is transferred to gateway using ZigBee communication link and from here meteorogical data and collected sensor data is forwarded to a central system through short message service via GSM. This centralised control system is supervised by the LabVIEW [87] programming which helps in storing the data into 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 static sensor network in which we have tried to integrate a system that measures all the major pollutant in the city of Prince George and also providing AQHI and AQI values. Unlike the other system mentioned in the literature our main focus is to give a user specific data for better understanding of pollution. We have also tried to implement calibration procedure to ensure the quality of data.

2.5 Summary

In this chapter the research done in sensor network for understanding the air quality is categorized into four. We went through the system which is attched to a vehicle for understanding the pollutant concentration and gets categorized as vehicular sensor network. This category provides great mobility but at the same time accumalation of redundant data is high. Next category we mentioned is the sensors which could be worn or attached to a person. This gives a better understanding of individual health effects of 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 performs 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 static sensor network. Our research work falls under this section and we focus not just on collecting pollutant value but also 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 [88]. 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 [89]. 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 [90].

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) [91] which introduced a tool called 'Macro

Analysis Tool' (MAT) for performing comparisons of air sensor data with reference data and interpreting the results [92].

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 [93]. The Air Sensor guidebook [92] 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" [94] and is obtained by linar regression [95]. 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 [96]. 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 [97] 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 [98].

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 [97]. 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) [97]. The slope of the graph shows the similarity or dif-

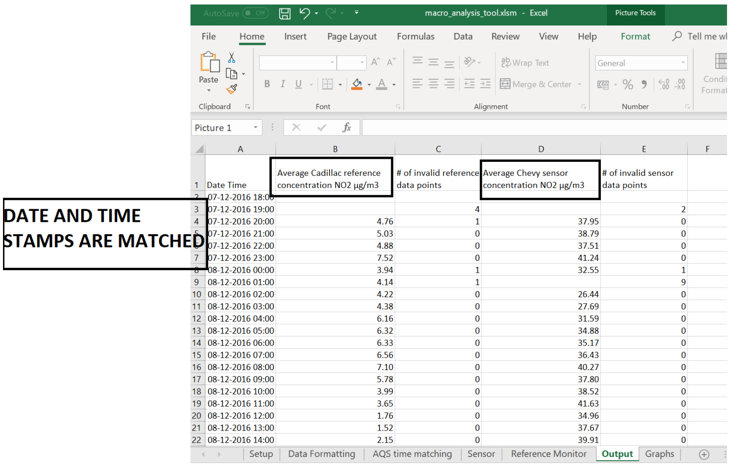

Figure 3.1: MAT Output

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

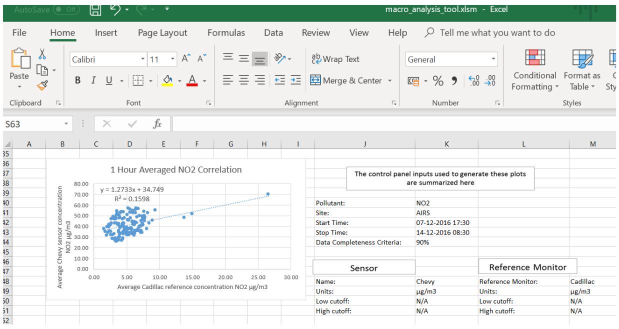

Figure 3.2: Correlation Graph

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 [99]. 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

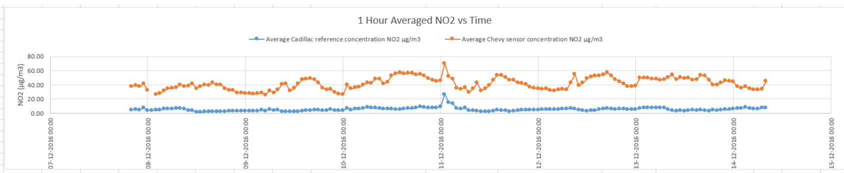

Figure 3.3: Time-Series Graph

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) [95]. 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.

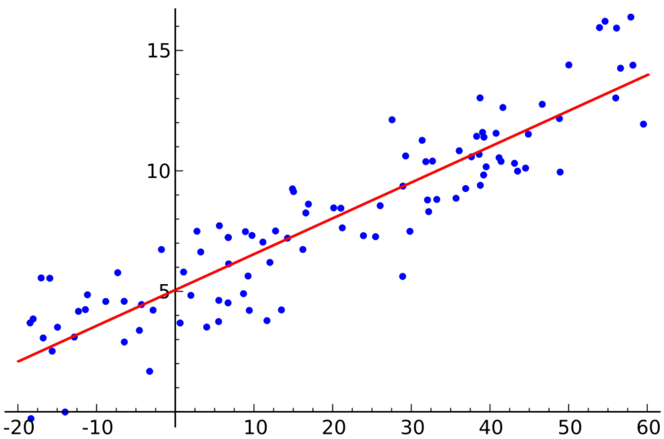

Figure 3.4: Linear Regression Model [96]

The method of Least Squares is a procedure to determine the best fit line to data [100] 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 [101] [102]. The line drawn will have a slope m and is given by the formula

$$m = \frac{\sum_i[(x_i - \bar{x})(y_i - \bar{y})]}{[\sum_i (x_i - \bar{x})^2]} \text{ [103] [104] [95]}$$

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

$$C = \bar{y} - m\bar{x} \text{ [103] [105]}$$

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 [103]. The equation for finding the regression value is

$$R^2 = \frac{\sum_i[(x_i - \bar{x})(y_i - \bar{y})]}{\sqrt{[\sum_i (x_i - \bar{x})^2 [\sum_i (y_i - \bar{y})^2]]}} \text{ [103]}$$

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 [95] 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

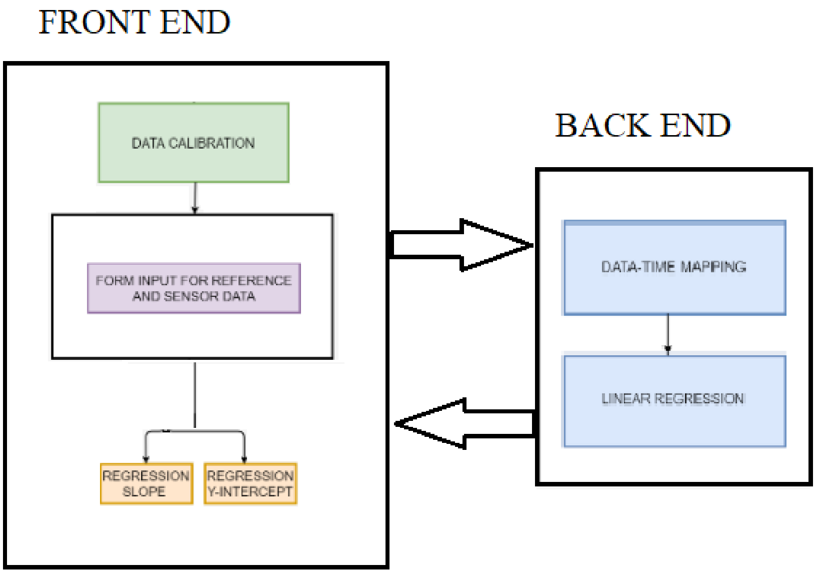

Figure 3.5: Framework of Calibration tool

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 [106]. 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 [107]. 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) [92] 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 [108] and Air Quality Index (AQI) which gives the level of air quality status in an area [109].

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 [110]. Industrial and vehicles release greenhouse emissions which are largely responsible for air pollution [111]. 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.

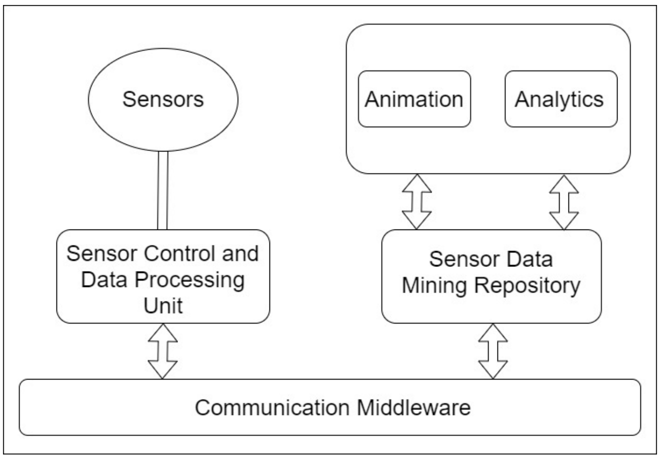

Figure 4.1: System Architecture

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 [112]:

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.

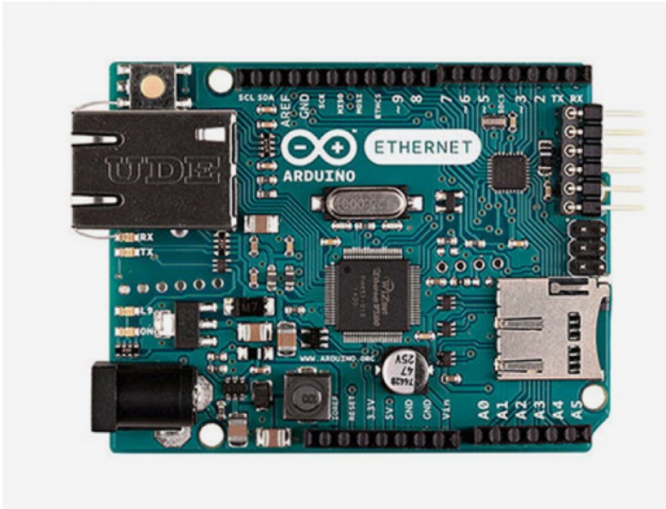

Figure 4.2: Arduino Ethernet Board

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 [113] 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 [114]. 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 [115].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 [116]. 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 [117]. 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

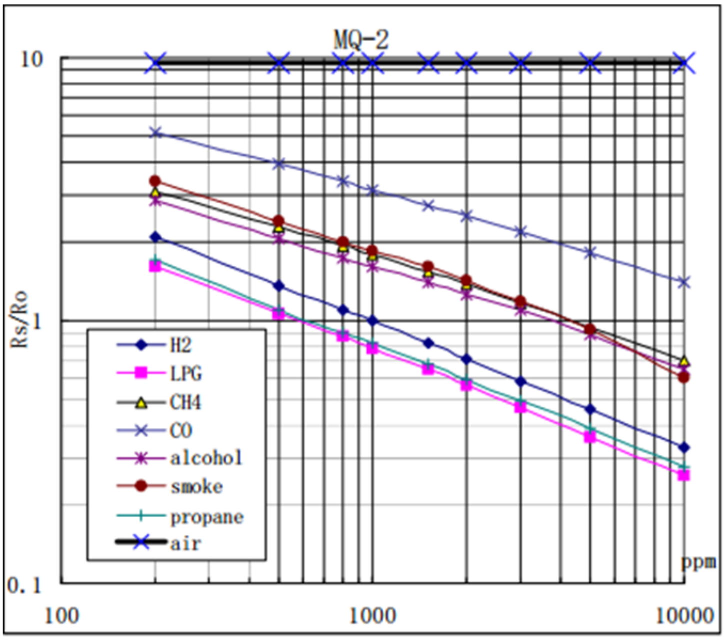

Figure 4.3: Sensitivity characteristics curve [115]

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 [118]. The circuit generates a measurable signal known as Low Pulse Occupancy (LPO) which is proportional to PM concentration [119]. 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 [120]. 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

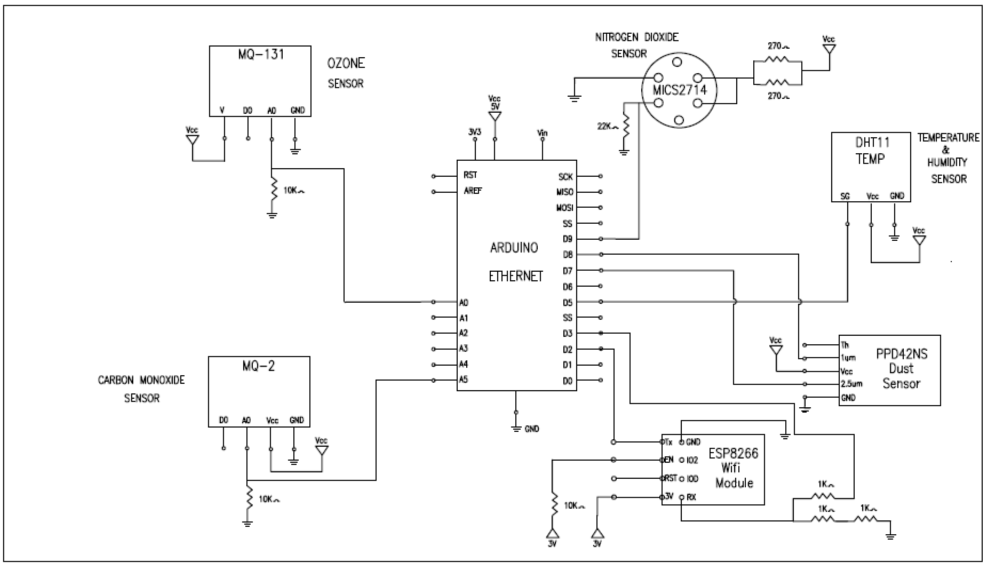

Figure 4.4: Circuit daigram of air pollution system

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 [121].

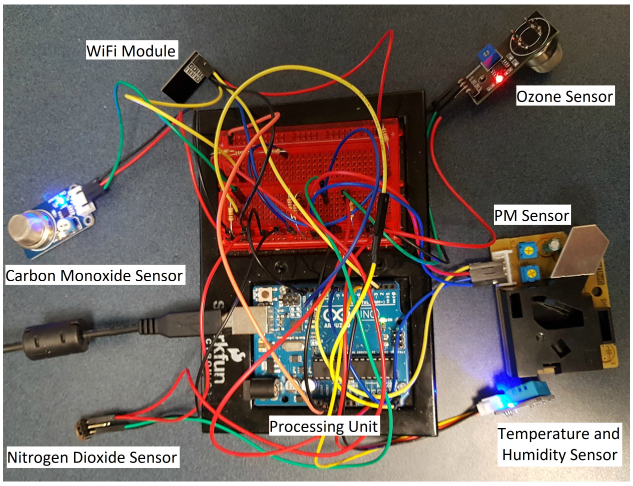

Figure 4.5: Prototype Implementation

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.

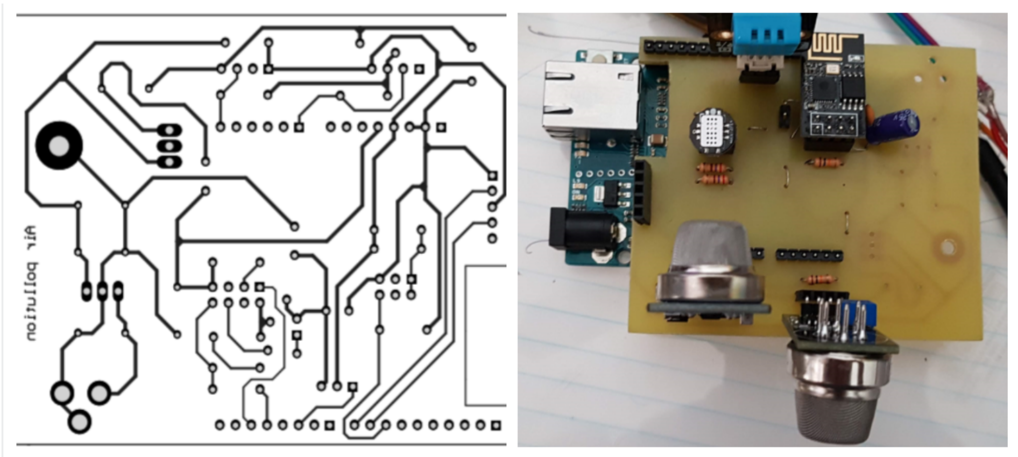

Figure 4.6: Printed Circuit Board

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" [122].

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 [123], 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 [123] 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 [124].

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

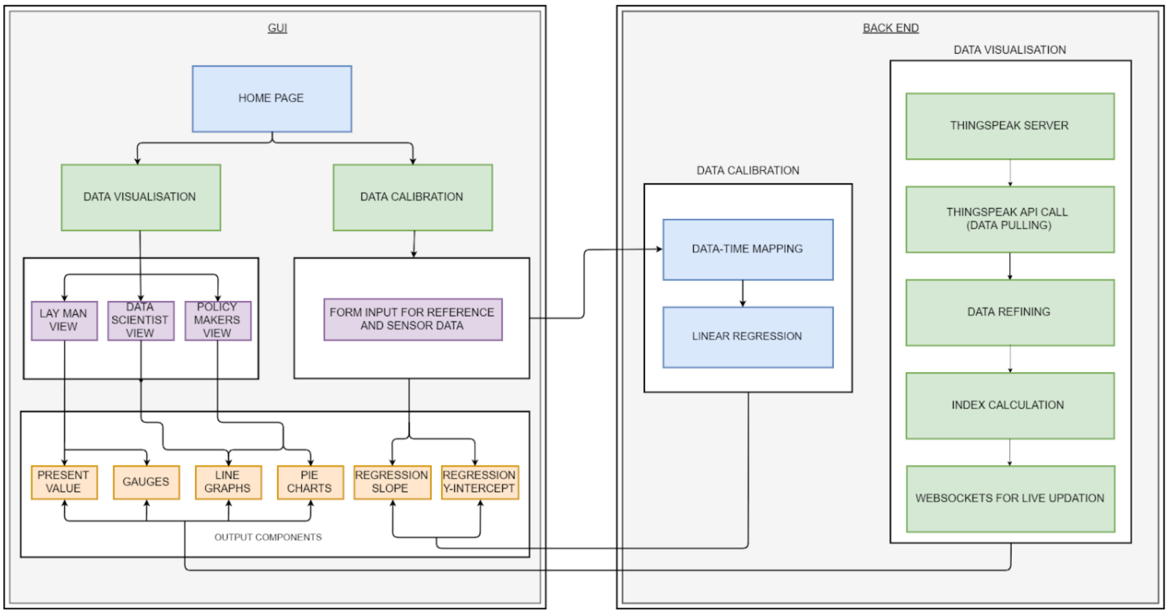

Figure 4.7: Software Architecture

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

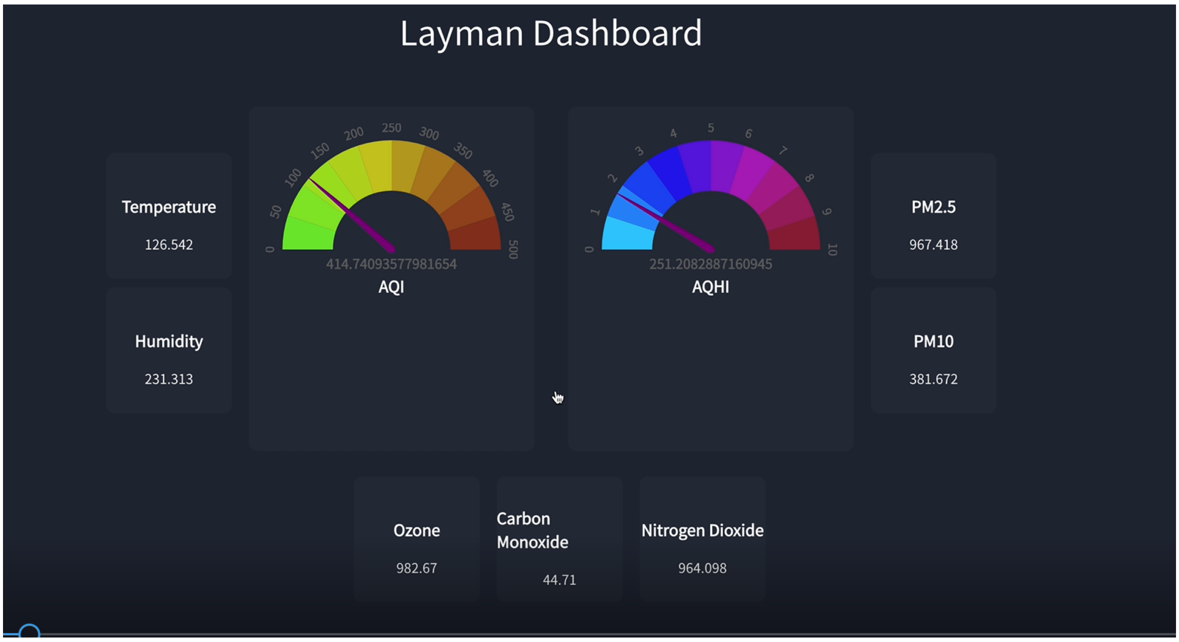

Figure 4.8: Lay man view

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

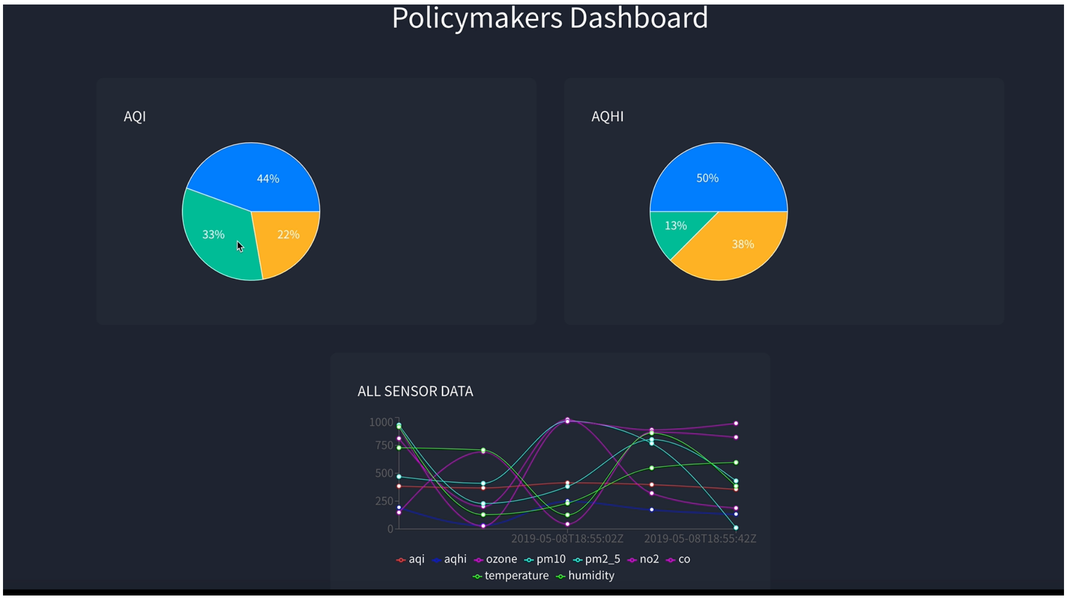

Figure 4.10: Officials view

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 [122] [125], 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 [126]. This is basically a paid visualization service that allows the system to aggregate, analyze, visualize, and store the sensor data

[126]. 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 six days in University Heights, Prince George. 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 collected values in ThingSpeak database were compared to the reference values located in

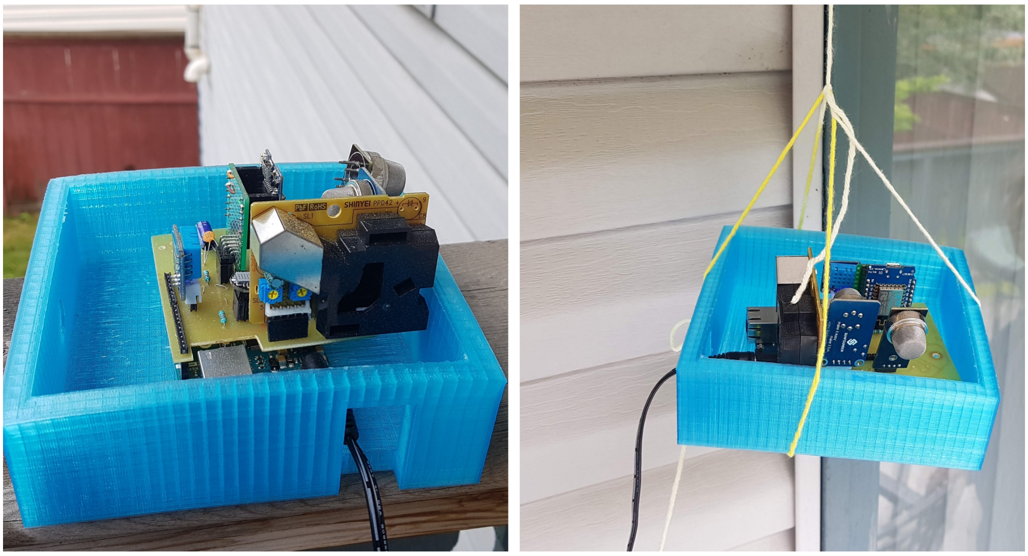

Figure 5.1: Deployed System at University Heights, Prince George

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 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.

5.2.1 Ozone

The ground level ozne 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 [127].The reference system uses an API model 400 ozone monitor the city measurement [128].The figure 5.2 shows the picture of the Ozone sensor used for measurement at the reference station as well as in our low cost sensor system.

API MODEL 400 OZONE MONITOR

MQ 131 OZONE SENSOR

Figure 5.2: 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 5.3 and 5.4 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 decreses to 6.32 ppb at 5:00 am. After this the value keeps on incresing 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 .

The Graph 5.3 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 5.4 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 updates with new regression equation so as to provide the

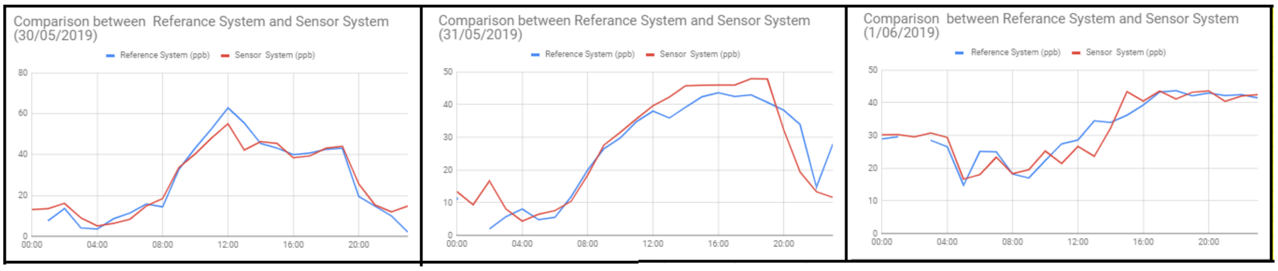

Figure 5.3: Comparison between Ozone values from sensor system and reference system from 30/05/2019 to 01/06/2019

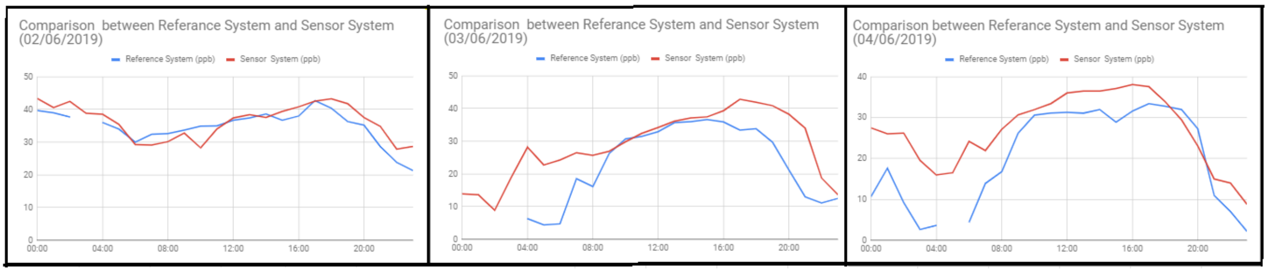

Figure 5.4: Comparison between Ozone values from sensor system and reference system from 02/06/2019 to 04/06/2019

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 air the need for calibration should be considered as a priority.

5.2.2 Nitrogen Dioxide

Nitrogen dioxide is found in urban areas which penitrates 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 [14] [129]. 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 referance system located in Prince George plaza 400 is API NO_x monitor [128] which uses chemiluminesence principle to measure the pollutant . The figure 5.5 shows the image of both the sensors for detecting the pollutant.

Figure 5.5: 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 5.6 and 5.7.

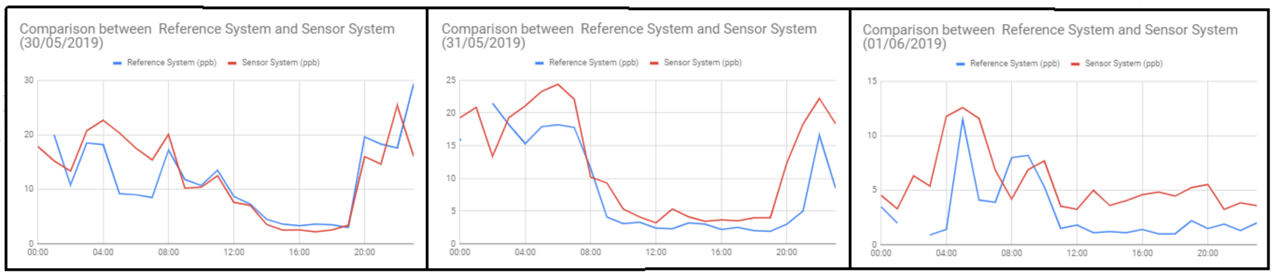

Figure 5.6: Comparison between Nitrogen Dioxide values from sensor system and reference system from 30/05/2019 to 01/06/2019

The maximum value measured from our sensor system was 25.39 ppb on the first day. 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 referance system but for the first three days the trend is followed. At the same time it can also be seen in the figure 5.7 that the values from both the system have less similarity.

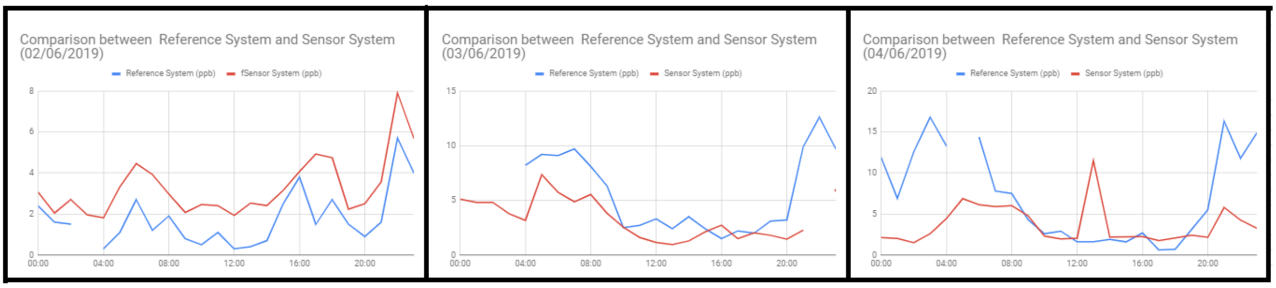

Figure 5.7: Comparison between Nitrogen Dioxide values from sensor system and reference system from 02/06/2019 to 04/06/2019

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 oxide can be because of less or no solar radiation in the early morning and late night [128] [130]. 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 [131] [128]. This can be clearly seen in the graphs in both referance value as well as in our sensor value. Another resaon 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.

5.2.3 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 [132]. 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 [131]. In prince george particulate matter pollution is a serious concern and variety of studies are going under this category.

Figure 5.8: 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 [131]. 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 [128]. The figure 5.8 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 5.9 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 [128].

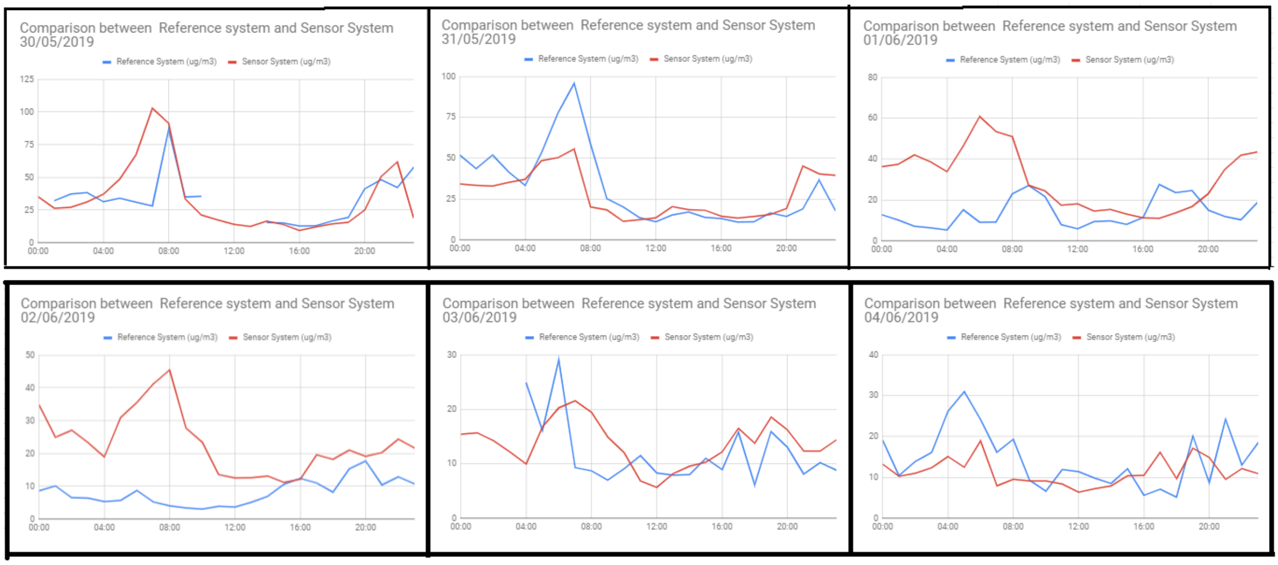

Figure 5.9: Comparison between PM_{10} values from sensor system and reference system from 30/05/2019 to 04/06/2019

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 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 inahling these particles can causes cardivascular diseases and other breathing problem. From the graph shown in figure 5.10 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.

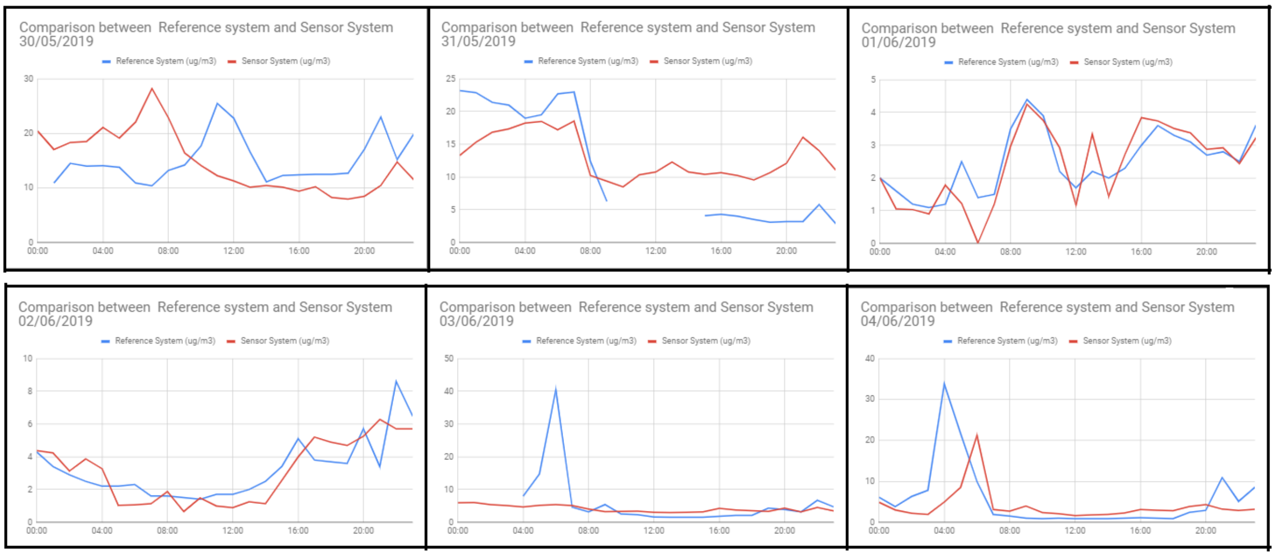

Figure 5.10: Comparison between $PM_{2.5}$ values from sensor system and reference system from 30/05/2019 to 01/06/2019

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

5.2.4 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 [133]. 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.

Bibliography

[1] Wikipedia. Natural Environment. https://en.wikipedia.org/wiki/Natural_environment, 2017. [Online; accessed 26-January-2018].

[2] Ioannis Manisalidis, Elisavet Stavropoulou, Agathangelos Stavropoulos, and Eugenia Bezirtzoglou. Environmental and Health Impacts of Air Pollution: A Review. *Frontiers in Public Health*, 8(February):1–13, 2020.

[3] Wikipedia. Persistent organic pollutant. https://en.wikipedia.org/wiki/Persistent_organic_pollutant, 2013. [Online; accessed 10-February-2019].

[4] J Ritter, L., Solomon, K.R. & Forget. Persistent organic pollutants: An assessment report on DDT, aldrin, dieldrin, endrin, chlordane, heptachlor, hexachlorobenzene, mirex, toxaphene, PCBs, dioxins and furans. Report for the International Programme on Chemical Safety (IPCS) within the framewo. page 43 pp., 2005.

[5] Health Effects Institute. State of Global Air 2017. *Health Effects Institute*, page 15, 2017.

[6] World Health Organization. How air pollution is destroying our health. https://www.who.int/air-pollution/news-and-events/how-air-pollution-is-destroying-our-health, 2019. [Online; accessed 04-January-2019].

[7] WHO. Preventing disease through healthy environments exposure to air pollution: A major public health concern. 2010.

[8] Daniel Vallero. Tool Steel - an overview (pdf) | ScienceDirect Topics. *Fundamentals of Air Pollution (Fifth Edition)*, pages 1–10, 2014.

[9] OAR US EPA. NAAQS Table.

[10] Definition of National Ambient Air Quality Standards (NAAQS). *ohioepa.custhelp.com*.

[11] H Chen and R Copes. *Review of Air Quality Index and Air Quality Health Index*. 2013.

[12] William E. Wilson and Helen H. Suh. Fine particles and coarse particles: Concentration relationships relevant to epidemiologic studies. *Journal of the Air and Waste Management Association*, 47(12):1238–1249, 1997.

[13] C.M. Payus, A.T. Vasu Thevan, and J. Sentian. Impact of school traffic on outdoor carbon monoxide levels. *City and Environment Interactions*, 4(2019):100032, 2019.

[14] Heidi Salonen, Tunga Salthammer, and Lidia Morawska. Human exposure to NO2 in school and office indoor environments. *Environment International*, 130(May):104887, 2019.

[15] United states Environmental Protection Agency. Ground-level ozone basics. `https://www.epa.gov/ground-level-ozone-pollution/ground-level-ozone-basics#wwh`, 2018.

[16] Nikhil Soni and Neetishree Soni. Benefits of pedestrianization and warrants to pedestrianize an area. *Land Use Policy*, 57:139–150, 2016.

[17] Government of India and Forests & Climate Change Ministry of Environment. National Air Quality Index. page 58, 2014.

[18] Frequently Asked Questions Air Quality Health Index. The air quality health index. *Air Quality health index FAQ*.

[19] Rundong Tian, Christine Dierk, Christopher Myers, and Eric Paulos. MyPart: Personal, Portable, Accurate Airborne Particle Counting. *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pages 1338–1348, 2016.

[20] M Artha P Atricia Sierra-vargas and L U I S M Teran. INVITED REVIEW SERIES : AIR POLLUTION AND LUNG HEALTH Air pollution : Impact and prevention. (January), 2012.

[21] Farideh Golbabaei, Hamid Hassani, Asghar Ghahri, and Mirghani Seyed Someah. Risk Assessment of Exposure to Gases Released by Welding Processes in Iranian Natural Gas Transmission Pipelines Industry. 4(2):6–9, 2012.

[22] Morton Lippmann. Health Effects Of Ozone A Critical Review. *Journal of the Air Pollution Control Association*, 39(5):672–695, 1989.

[23] Elias Castanas Marilena Kampa. Human health effects of air pollution. 151:362–367, 2007.

[24] Rinkesh. What is Air pollution? `https://www.conserve-energy-future.com/causes-effects-solutions-of-air-pollution.php`, 2013. [Online; accessed 2-June-2018].

[25] K Heidorn. A Chronology of Important Events in the History of Air Pollution Meteorology to 1970. *Bulletin of the American Meteorological Society*, 59(12):1589–1597, 1978.

[26] Timothy Hatton. Quantifying the impact of smoke pollution on health in the 19th century. `https://voxeu.org/article/smoke-pollution-and-health-19th-century`, 2017. [Online; accessed 26-January-2019].

[27] Viktor P Ál. The Environmental Consequences of Industrialization in Western European Core Countries and the Borsod Basin of Hungary , 1850 – 1945 : A Comparative Outline. 3:75–84, 2016.

[28] Wikipedia. Great Smog of London. `https://en.wikipedia.org/wiki/Great_Smog_of_London`, 2019. [Online; accessed 26-January-2019].

[29] Wikipedia. Air Pollution Control Act. `https://en.wikipedia.org/wiki/Air_Pollution_Control_Act`, 2018. [Online; accessed 26-January-2019].

[30] K Balakrishnan, M Brauer, G Chen, and J Chow. *To Humans Outdoor Air Pollution*, volume 109. 2015.

[31] Eddie Salter. Active versus Passive Air Sampling . `https://www.envirotech-online.com/article/health-and-safety/10/skc/active-versus-passive-air-sampling-eddie-salter/923`, 2011. [Online; accessed 26-January-2019].

[32] Ministry of Environment. 4 How to Monitor? – Monitoring Methods | Ministry for the Environment, 2009.

[33] Daniel C Mussatti, Margaret Groeber, and Dan Maloney. Generic Equipment and Devices for continous emission minitoring system. *Evironment Protection Agency*, pages 4–1 – 4–40, 2000.

[34] Li Sun, Ka Chun Wong, Peng Wei, Sheng Ye, Hao Huang, Fenhuan Yang, Dane Westerdahl, Peter K.K. Louie, Connie W.Y. Luk, and Zhi Ning. Development and application of a next generation air sensor network for the Hong Kong marathon 2015 air quality monitoring. *Sensors (Switzerland)*, 16(2), 2016.

[35] Abdullah Kadri, Elias Yaacoub, Mohammed Mushtaha, and Adnan Abu-Dayya. Wireless sensor network for real-time air pollution monitoring. *2013 1st International Conference on Communications, Signal Processing and Their Applications, ICCSPA 2013*, pages 1–5, 2013.

[36] David Hasenfratz and Enabling. *Enabling Large-Scale Urban Air Quality*. 2015.

[37] Pollution Prevention, Air Protection, Omineca-peace Region, Prince George, and British Columbia. 2000 ANNUAL AIR QUALITY REPORT. (April), 2000.

[38] Northern Health Authority. PRINCE GEORGE MOBILE MONITORING PRINCE GEORGE MOBILE MONITORING. page 77, 2011.

[39] British Columbia Ministry of Environment. Air Quality in Prince George, Summary Report. (June 2016):21, 2016.

[40] Government of British Columbia. Prince george plaza 400 - air monitoring station. `http://www.env.gov.bc.ca/epd/bcairquality/data/station.html?id=0450307`, 2020.

[41] Gary Anthes. Open source software no longer optional. *Communications of the ACM*, 59(8):15–17, 2016.

[42] Kavi Kumar Khedo and Vishwakarma Chikhooreeah. Low-Cost Energy-Efficient Air Quality Monitoring System Using Wireless Sensor Network. *Wireless Sensor Networks - Insights and Innovations*, (October), 2017.

[43] Yang Huang Liu, Liang Hu, Disheng Yang, and Hengchang. Air-Sense: indoor environment monitoring evaluation system based on ZigBee network. *IOP Conference Series: Earth and Environmental Science*, 81(1):12208, 2017.

[44] Wei Yi, Kin Lo, Terrence Mak, Kwong Leung, Yee Leung, and Mei Meng. *A Survey of Wireless Sensor Network Based Air Pollution Monitoring Systems*, volume 15. 2015.

[45] Movva Pavani and P. Trinatha Rao. Urban air pollution monitoring using wireless sensor networks: A comprehensive review. *International Journal of Communication Networks and Information Security*, 9(3):439–449, 2017.

[46] Anthony Downs. Traffic: Wht its getting worse, What givernment can do. (January), 2004.

[47] Shu Chiung Hu, You Chiun Wang, Chiuan Yu Huang, and Yu Chee Tseng. A vehicular wireless sensor network for CO2monitoring. *Proceedings of IEEE Sensors*, pages 1498–1501, 2009.

[48] Shu Chiung Hu, You Chiun Wang, Chiuan Yu Huang, and Yu Chee Tseng. Measuring air quality in city areas by vehicular wireless sensor networks. *Journal of Systems and Software*, 84(11):2005–2012, 2011.

[49] Péter Völgyesi, András Nádas, Xenofon Koutsoukos, and Ákos Lédeczi. Air quality monitoring with SensorMap. *Proceedings - 2008 International Conference on Information Processing in Sensor Networks, IPSN 2008*, pages 529–530, 2008.

[50] Srinivas Devarakonda, Parveen Sevusu, Hongzhang Liu, Ruilin Liu, Liviu Iftode, and Badri Nath. Real-time Air Quality Monitoring Through Mobile Sensing in Metropolitan Areas. 2013.

[51] Debanshee Saha. IoT based Air Quality Monitoring System using Wireless Sensors deployed in Public Bus Services. 2017.

[52] Yoshinari Shirai, Yasue Kishino, Futoshi Naya, and Yutaka Yanagisawa. Toward On-Demand Urban Air Quality Monitoring using Public Vehicles. *IWSC@Middleware*, pages 1:1–1:6, 2016.

[53] Chaosheng Xiang, Xiaofeng Liu, Aimin Jiang, Bin Yan, and Jing Xia. Poster: A Bicycle-borne Sensor Network for Monitoring Urban Air Quality. *Mobisys'16: Companion Companion Publication of the 14Th Annual International Conference on Mobile Systems, Applications, and Services*, (March):88, 2016.

[54] Xiaofeng Liu, Bin Li, Aimin Jiang, Shixin Qi, Chaosheng Xiang, and Ning Xu. A bicycle-borne sensor for monitoring air pollution near roadways. *2015 IEEE International Conference on Consumer Electronics - Taiwan, ICCE-TW 2015*, (January 2017):166–167, 2015.

[55] S. D. Zhi, Y. B. Wei, and Z. H. Yu. Air Quality Monitoring Platform based on Remote Unmanned Aerial Vehicle with Wireless Communication. *Proceedings of the International Conference on Future Networks and Distributed Systems - ICFNDS '17*, (July):1–7, 2017.

[56] Evi Dons, Michelle Laeremans, Juan Pablo Orjuela, Ione Avila-Palencia, Glòria Carrasco-Turigas, Tom Cole-Hunter, Esther Anaya-Boig, Arnout Standaert, Patrick De Boever, Tim Nawrot, Thomas Götschi, Audrey De Nazelle, Mark Nieuwenhuijsen, and Luc Int Panis. Wearable Sensors for Personal Monitoring and Estimation of Inhaled Traffic-Related Air Pollution: Evaluation of Methods. *Environmental Science and Technology*, 51(3):1859–1867, 2017.

[57] Ke Hu, Timothy Davison, Ashfaqur Rahman, and Vijay Sivaraman. Air Pollution Exposure Estimation and Finding Association with Human Activity using Wearable Sensor Network. pages 48–55, 2015.

[58] Alyssa I. Robinson Fletcher, Richard Ribón Nicolas M. Oreskovic, M.D. Design and Clinical Feasibility of Personal Wearable Monitor for Measurement of Activity and Environmental Exposure. pages 874–877, 2015.

[59] Piero Zappi, Elizabeth Bales, Jing Hong Park, William Griswold, and Tajana Šimunić Rosing. The CitiSense Air Quality Monitoring Mobile Sensor Node. *Proceedings of the 11th ACM/IEEE Conference on Information Processing in Sensor Networks, Beijing, China*, (January), 2012.

[60] Sunyoung Kim, Eric Paulos, and Mark D Gross. WearAir: Expressive T-shirts for Air Quality Sensing. *Proc. TEI '10*, pages 295–296, 2010.

[61] Ke Hu, Yan Wang, Ashfaqur Rahman, and Vijay Sivaraman. Personalising pollution exposure estimates using wearable activity sensors. *IEEE ISSNIP 2014 - 2014 IEEE 9th International Conference on Intelligent Sensors, Sensor Networks and Information Processing, Conference Proceedings*, (April):21–24, 2014.

[62] Gabriele Valli, Mattia Internullo, Alessandro M. Ferrazza, Paolo Onorati, Annalisa Cogo, and Paolo Palange. Minute ventilation and heart rate relationship for estimation of the ventilatory compensation point at high altitude: A pilot study. *Extreme Physiology and Medicine*, 2(1):1, 2013.

[63] brian p rubin. Tzoa's Wearable Enviro-Tracker Wants To Clear The Air. `https://readwrite.com/2015/05/20/tzoa-wearable-air-quality-sensor-crowdfunding-indiegogo/`, 2015. [Online; accessed 06-March-2019].

[64] Chris C. Lim Michael Heimbinder, Raymond Yap. The aircasting platform. `http://aircasting.org/`, 2006. [Online; accessed 01-January-2019].

[65] Dan Han. Air Quality Monitoring , Fushun-Kokkola. pages 1–2, 2010.

[66] Aircasting Luminescence, New York Hall, The Aircasting Luminescence, Iem Heng, Raymond Yap, City Tech, Andy Zhang, The Aircasting, and Luminescent Vest. Make Your Own AirCasting Luminescent Apparel.

[67] Salil S. Kanhere. Participatory sensing: Crowdsourcing data from mobile smartphones in urban spaces. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 7753 LNCS:19–26, 2013.

[68] Vijay Sivaraman, James Carrapetta, Ke Hu, and Blanca Gallego Luxan. HazeWatch: A participatory sensor system for monitoring air pollution in Sydney. *Proceedings - Conference on Local Computer Networks, LCN*, pages 56–64, 2013.

[69] Duanping Liao, Donna J. Peuquet, Yinkang Duan, Eric A. Whitsel, Jianwei Dou, Richard L. Smith, Hung Mo Lin, Jiu Chiuan Chen, and Gerardo Heiss. GIS approaches for the estimation of residential-level ambient PM concentrations. *Environmental Health Perspectives*, 114(9):1374–1380, 2006.

[70] P Dutta, Paul M Aoki, N Kumar, and A Mainwaring. Common Sense: Participatory urban sensing using a network of handheld air quality monitors. *SenSys '09*, pages 349–350, 2009.

[71] Tarek Abdelzaher, Yaw Anokwa, Péter Boda, Jeff Burke, Deborah Estrin, Leonidas Guibas, Aman Kansal, Samuel Madden, and Jim Reich. Mobiscopes for human spaces. *IEEE Pervasive Computing*, 6(2):20–29, 2007.

[72] P M Aoki, R J Honicky, A Mainwaring, C Myers, E Paulos, S Subramanian, and A Woodruff. Common sense: Mobile environmental sensing platforms to support community action and citizen science. *Adjunct Proceedings Ubicomp 2008*, (October):Paper 201 OR – Human Computer Interaction Institu, 2008.

[73] Karl Aberer, Saket Sathe, Dipanjan Chakraborty, Alcherio Martinoli, Guillermo Barrenetxea, Boi Faltings, and Lothar Thiele. OpenSense. (January):39–42, 2010.

[74] David Hasenfratz, Olga Saukh, Silvan Sturzenegger, and Lothar Thiele. Participatory air pollution monitoring using smartphones. *Proc. 1st Int'l Workshop on Mobile Sensing: From Smartphones and Wearables to Big Data*, pages 1–5, 2012.

[75] Bratislav Predic, Zhixian Yan, Julien Eberle, Dragan Stojanovic, and Karl Aberer. ExposureSense: Integrating daily activities with air quality using mobile participatory sensing. *2013 IEEE International Conference on Pervasive Computing and Communications Workshops, PerCom Workshops 2013*, (3):303–305, 2013.

[76] Alfredo J. Perez, Miguel A. Labrador, and Sean J. Barbeau. G-Sense: A scalable architecture for global sensing and monitoring. *IEEE Network*, 24(4):57–64, 2010.

[77] Diego Mendez, Alfredo J. Perez, Miguel A. Labrador, and Juan Jose Marron. P-Sense: A participatory sensing system for air pollution monitoring and control. *2011 IEEE International Conference on Pervasive Computing and Communications Workshops, PERCOM Workshops 2011*, pages 344–347, 2011.

[78] Man Wong, Tsan Yip, and Esmond Mok. Development of a Personal Integrated Environmental Monitoring System. *Sensors*, 14(11):22065–22081, 2014.

[79] Kavi K. Khedo, Rajiv Perseedoss, and Avinash Mungur. A Wireless Sensor Network Air Pollution Monitoring System. *International Journal of Wireless & Mobile Networks*, 2(2):31–45, 2010.

[80] B. Fang, Q. Xu, T. Park, and M. Zhang. AirSense: An intelligent home-based sensing system for indoor air quality analytics. *UbiComp 2016 - Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing*, pages 109–119, 2016.

[81] M. F.M. Firdhous, B. H. Sudantha, and P. M. Karunaratne. IoT enabled proactive indoor air quality monitoring system for sustainable health management. *Proceedings of the 2017 2nd International Conference on Computing and Communications Technologies, ICCCT 2017*, (February):216–221, 2017.

[82] Rohan Narayana Murty, Geoffrey Mainland, Ian Rose, Atanu Roy Chowdhury, Abhimanyu Gosain, Josh Bers, and Matt Welsh. CitySense: An urban-scale wireless sensor network and testbed. *2008 IEEE International Conference on Technologies for Homeland Security, HST'08*, pages 583–588, 2008.

[83] John Bicket, Daniel Aguayo, Sanjit Biswas, and Robert Morris. Architecture and evaluation of an unplanned 802.11b mesh network. page 31, 2005.

[84] Joseph Camp, Joshua Robinson, Christopher Steger, and Edward Knightly. Measurement driven deployment of a two-tier urban mesh access network. page 96, 2006.

[85] CUWin Foundation. open source community hosting that makes a difference. `https://www.cuwireless.net/`, 2006. [Online; accessed 10-April-2019].

[86] Jen Hao Liu, Yu Fan Chen, Tzu Shiang Lin, Da Wei Lai, Tzai Hung Wen, Chih Hong Sun, Jehn Yih Juang, and Joe Air Jiang. Developed urban air quality monitoring system based on wireless sensor networks. *Proceedings of the International Conference on Sensing Technology, ICST*, pages 549–554, 2011.

[87] NATIONAL INSTRUMENTS. LabVIEW. (June):1–89, 2013.

[88] Eric S Hall, Surender M Kaushik, Robert W Vanderpool, Rachelle M Duvall, Melinda R Beaver, Russell W Long, and Paul A Solomon. Federal Reference Method (FRM), Federal Equivalent Method (FEM), National Ambient Air Quality Standards (NAAQS), Sensors; Federal Reference Method (FRM), Federal Equivalent Method (FEM), National Ambient Air Quality Standards (NAAQS), Sensors. *American Journal of Environmental Engineering*, 4(6):147–154, 2014.

[89] Davis Kejuruteraan, Fakulti Tekn, NIST Engineering Statistics Handbook Jenny Wu (University of California). Instrument Calibration. pages 1–7, 2018.

[90] Ron Williams, Tim Watkins, and Russell Long. Low Cost Sensor Calibration Options The Straw-Man Approach. 2013.

[91] Ron Williams, Vasu J Kilaru, Emily G Snyder, Amanda Kaufman, Timothy Dye, Andrew Rutter, Ashley Russell, and Hilary Hafner. Air Sensor Guidebook. *Epa/600/R-14/159*, (1):1–5, 2014.

[92] U.S. Environmental Protection Agency. Macro Analysis Tool -MAT. https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=340520&Lab=NERL, 2018. [Online; accessed 04-December-2018].

[93] U.S. Environmental Protection Agency. Air Sensor Toolbox for Citizen Scientists, Researchers and Developers. https://www.epa.gov/air-sensor-toolbox, 2018. [Online; accessed 04-December-2018].

[94] Epa and Ord. Calibration Curves: Program Use/Needs Final. (October), 2010.

[95] Shaun Burke and High Wycombe. Regression and Calibration. pages 13–18.

[96] The free Encyclopedia Wikipedia. Linear regression. https://en.wikipedia.org/wiki/Linear_regression, 2018. [Online; accessed 04-December-2018].

[97] National Exposure Research Laboratory Office of Research and Development. How to Evaluate Low-Cost Sensors by Collocation with Federal Reference Method Monitors. pages 1–45, 2017.

[98] Instruction guide and macro analysis tool for community-led air monitoring. https://www.epa.gov/air-research/instruction-guide-and-macro-analysis-tool-community-led-air-monitoring, 2016. Accessed: 2018-12-06.

[99] Ron Williams. Emerging Sensor Technologies. 2018.

[100] S.Miller. The Method of Least Squares and Signal Analysis. pages 1–7, 1992.

[101] A. M. Almeida, M. M. Castel-Branco, and A. C. Falcão. Linear regression for calibration lines revisited: Weighting schemes for bioanalytical methods. *Journal of Chromatography B: Analytical Technologies in the Biomedical and Life Sciences*, 774(2):215–222, 2002.

[102] Wayne W Daniel and Chad Lee Cross. *Biostatistics: a foundation for analysis in the health sciences*. Wiley, 2018.

[103] D Stone and J Ellis. Calibration and Linear Regression Analysis: A Self-Guided Tutorial (Part 2). pages 1–7, 2001.

[104] Diana Arsova, Sofia Babanova, and Petko Mandjukov. Linear Calibration – Is It so Simple ? pages 35–42, 2009.

[105] David Harvey. 5.4: Linear Regression and Calibration Curves - Chemistry LibreTexts. *LibreTexts*, pages 1–12, 2016.

[106] Aaron Daly and Paolo Zannetti. An Introduction to Air Pollution – Definitions , Classifications , and History. pages 1–14, 2007.

[107] Emily G. Snyder, Timothy H. Watkins, Paul A. Solomon, Eben D. Thoma, Ronald W. Williams, Gayle S. W. Hagler, David Shelow, David A. Hindin, Vasu J. Kilaru, and Peter W. Preuss. The Changing Paradigm of Air Pollution Monitoring. *Environmental Science & Technology*, 47(20):11369–11377, 2013.

[108] Frequently Asked Questions. The air quality health index. *Air Quality health index FAQ*.

[109] J S Asha and P Sindhu. Website : www.ijirset.com Assessment of Air Quality in Two Cities of Kerala based on AQI by USEPA Method and. (2009):9284–9292, 2017.

[110] Debanshee Saha. IoT based Air Quality Monitoring System using Wireless Sensors deployed in Public Bus Services. 1952.

[111] Various Contributors. Essay on Air pollution: Introduction, Causes, Sources, Impact and Control Measures. 2013.

[112] Massimo Banzi and First Edition. *Getting started with Arduino*. :Books, an imprint of Maker Media, a division of O'Reilly Media, Inc., october 20 edition, 2008.

[113] Manuel Ruiz Guti. Arduino + Ethernet Shield. pages 1–42, 2017.

[114] Young Jin Jung, Yang Koo Lee, Dong Gyu Lee, Yongmi Lee, Silvia Nittel, Kate Beard, Kwang Woo Nam, and Keun Ho Ryu. Design of sensor data processing steps in an air pollution monitoring system. *Sensors*, 11(12):11235–11250, 2011.

[115] Technical Data. MQ-2 Semiconductor Sensor for Alcohol. *Structure*, pages 3–5, 2012.

[116] Vaibhav Jain. Insight - Learn the Working of a Gas Sensor. `https://www.engineersgarage.com/insight/how-gas-sensor-works`, 2013. [Online; accessed 10-November-2018].

[117] SGX Sensortech. SGX Sensortech Data Sheet MiCS-2714 MOS Sensor for Nitrogen Dioxide. pages 1–5.

[118] Tracy Allen. De-construction of the Shinyei PPD42NS dust sensor. (510):0–3, 2002.

[119] Joel Kuula, Timo Mäkelä, Risto Hillamo, and Hilkka Timonen. Response characterization of an inexpensive aerosol sensor. *Sensors (Switzerland)*, 17(12), 2017.

[120] Espressif Systems. ESP8266EX. pages 1–22, 2018.

[121] Ashlin Saju and Alex Aravind. A Cyber-Physical System for Pervasive Air Pollution Monitoring. pages 1–5, UNPUBLISHED-2018.

[122] Katherine Hepworth. Big Data Visualization : Promises & Pitfalls. pages 7–19.

[123] Mary R English. Who Are the Stakeholders in Environmental Risk Decisions? ... How Should They Be Involved? *Risk: Health, Safety & Environment*, 11(243):352–362, 2000.

[124] Ashlin Saju and Alex Aravind. Towards Effective Visualization of Air Quality Data. pages 1–6, UNPUBLISHED-2018.

[125] Alberto Cairo. Ethical Infographics. *Investigative Reporters and Editors, Inc. The IRE Journal*, 37(2):25–27, 2014.

[126] Thingsspeak. Things speak- IOT platform. `https://thingspeak.com/`, 2017. [Online; accessed 26-January-2018].

[127] Hanwei Henan Electronics Co. MQ131 Semiconductor Sensor for Ozone. pages 2–4, 2010.

[128] Ministry Environment. 2008 Annual Air Quality Report for the Prince George Airshed. *Sulphur*, (February), 2010.

[129] Government of Canada. Common air pollutants: nitrogen oxides. `https://www.canada.ca/en/environment-climate-change/services/air-pollution/pollutants/common-contaminants/nitrogen-oxides.html`, 2013.

[130] F O R Prince George. 2003 Annual Air Quality Report. (April), 2005.

[131] Environmental Quality Section MoE. 2010 Annual Air Quality Report. (June), 2012.

[132] Gary Champagne and Dennis Fudge. Prince George Air Quality Management Background Report. 1996.

[133] Government of Canada. About the air quality health index. `https://www.canada.ca/en/environment-climate-change/services/air-quality-health-index/about.html#What_is_AQHI`, 2019.