Ebru İçöz

DEVELOPMENT OF A SMART SENSOR SYSTEM TO DETECT AIR POLLUTION

AGU 2019

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A THESIS
SUBMITTED TO THE DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING
AND THE GRADUATE SCHOOL OF ENGINEERING AND SCIENCE
OF ABDULLAH GUL UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER'S

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SCIENTIFIC ETHICS COMPLIANCE

I hereby declare that all information in this document has been obtained in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all materials and results that are not original to this work.

Ebru İçöz

REGULATORY COMPLIANCE

M.Sc. thesis titled **"DEVELOPMENT OF A SMART SENSOR SYSTEM TO DETECT AIR POLLUTION"** has been prepared in accordance with the Thesis Writing Guidelines of the Abdullah Gül University, Graduate School of Engineering & Science.

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ACCEPTANCE AND APPROVAL

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ABSTRACT

DEVELOPMENT OF A SMART SENSOR SYSTEM TO DETECT AIR POLLUTION

Air pollution is one of the global problems of modern world. According to World Health Organization only 9% of the world's total population can breathe clean air. Particulate Matter, which is the mixture of liquid and solid particles having diameters less than 10 μm is one of the pollutants in air. Particulate Matter is mostly produced from burning reactions in factories, vehicles or homes. Several studies have shown the deleterious impact of particulate matter to public health and environment. The increase of particulate matter in air has been linked to many health problems such as lung disease, asthma, respiratory insufficiency, mortality in infants, heart attacks, cancer and etc. Developed countries have regulations for monitoring the air quality and conventional bulky stations are employed for that purpose. These stations are high-cost and they have limited spatial resolution. In order to overcome the limitations of existing monitoring systems, alternative approaches have been studied. In this study, an optical Particulate Matter sensor is designed, produced and tested for monitoring air quality. The developed system is low-cost and has high spatial resolution. The sensor network is able to communicate with cloud computing and allows remote data analysis. The developed sensor system is able to provide air quality data in correlation with the existing stations.

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May 2019

Keywords: *Air Pollution, Sensors, Cloud Computing, Optical Sensing, Particulate Matter.*

ÖZET

HAVA KİRLİLİĞİ ÖLÇÜMÜ İÇİN AKILLI SENSÖR SİSTEMİ GELİŞTİRİLMESİ

Hava kirliliği modern dünyanın global problemlerinden biridir. Dünya Sağlık Örgütünün verilerine göre dünya nüfusunun ancak %9'u temiz hava soluyabilmektedir. Parçacık Madde 10 µm'dan küçük sıvı ve katı parçacıklardan oluşur ve hava kirliliğini oluşturan kirleticilerden biridir. Parçacık Maddeler çoğunlukla fabrikalardaki, taşıtlardaki ya da evlerdeki yanma reaksiyonları sonucu oluşmaktadır. Parçacık Maddelerin sağlığa zararlı etkileri birçok çalışmada gösterilmiştir. Parçacık Maddelerin miktarının hava da artması ile akciğer hastalıkları, astım, solunum yetmezliği, bebek ölümleri, kalp krizi ve kanser gibi birçok sağlık sorunun ilişkili olduğu gösterilmiştir. Gelişmiş ülkelerin yasaları hava kalitesinin sürekli izlenmesini şart koşmaktadır. Bu amaçla yüksek maliyetli istasyonlar kullanılmaktadır. Bu istasyonların bir diğer dezavantajı da sınırlı sahaya ait bilgi verebilmesidir. Bu kısıtlamaların üstesinden gelmek için alternatif yaklaşımlar çalışılmaktadır. Bu çalışmada da optik tabanlı Parçacık Madde sensörü tasarlanmış, üretilmiş ve test edilmiştir. Geliştirilen sistem düşük maliyetli ve yüksek saha çözünürlüğüne sahiptir. Kurulan sensör ağı bulut bilişime veri aktarımı yapabilmekte ve uzaktan veri analizine olanak sağlamaktadır. Geliştirilen sistem halihazırdaki istasyonlar ile doğruluğu uyumlu veri üretebilmekte ve böylece hava kalitesinin izlenmesinde kullanabilecektir.

Elektrik ve Bilgisayar Mühendisliği Ana Bilim Dalı, Yüksek Lisans Programı
Tez Yöneticisi: Dr. Öğr. Üyesi Gülay Yalçın

Mayıs 2019

Anahtar kelimeler: Hava Kirliliği, Sensörler, Bulut Bilişim, Optik Algılama, Parçacık Madde.

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I dedicate this thesis to my family

Zeynep Azra, Mustafa Çağrı and Kutay

Chapter 1

Introduction

According to World Health Organization (WHO) ambient air pollution results in 4.2 million deaths every year and 91% of the world's population lives in places where the air quality is low compared to safety levels determined by WHO. Heart disease, stroke, chronic pulmonary disease, lung cancer and acute respiratory infections are the main diseases, which are associated with the air pollution [1]. Common air pollutants are particulate matter (PM), ozone (O_3), nitrogen dioxide (NO_2), carbon monoxide (CO), volatile organic compounds (VOCs) and sulphur dioxide (SO_2) [2][3].

PM is a complex mixture of liquid and solid particles of different sizes suspended in the air and some of them are produced during the burning of fossil fuels; coal, gasoline, diesel fuels and wood. Also, dust, sea salt in coastal areas, pollens, spores and debris in air are also considered PM. Examples showing the variety of PM composition is reported in [4], [5], measurements in Barcelona metro system showed that PM was composed of Ba, Fe, Cu, Mn, Cr, Sb, As, Mo, Co, Sr, and hematite [4] whereas measurements in Thessaloniki showed that PM was composed of water-soluble ions such Na^+, K^+, NH_4^+, Ca^{2+}, Mg^{2+}, Cl^-, NO_3^-, SO_4^- [5].

The air pollution in 20 megacities of the world is investigated in [6] and it was suggested that to reduce the severe health risks, the air pollution has to be reduced significantly and monitoring systems should be improved. Like many national regulations, European Union policies established the standards for the equipment monitoring the air quality [7]. The high cost (10000£-15000£) of these instruments [8] resulted in developing low-cost alternatives [9].

The high cost of conventional air quality measurement equipment and harmful impact of air pollution on human health directed researchers to develop alternative air quality measurement systems which should be low-cost but sufficiently sensitive.

Aim of this project: Our goal is to develop a low-cost optical PM sensor which can communicate with cloud computing and increase spatial resolution for air quality measurements.

This thesis has five sections; the first section introduces PM and related health impacts. The second section introduces state of the art measurement techniques. The third section explains the principles of optical sensor, simulation results and design of the optical sensor. The forth part explains the sensor system and cloud computing along with the measurements. The fifth part includes conclusion and future work.

1.1 Particulate Matter

The earth's atmosphere has layers and atmospheric temperature and substance density vary with attitude (Figure 1.1.1). We live in troposphere and air pollution scientists mainly are interested in this layer. However upper layers are also investigated since these layers absorb or scatter solar energy, global air transportation, debris of volcanic eruptions occur in these layers and have impact on air pollution.

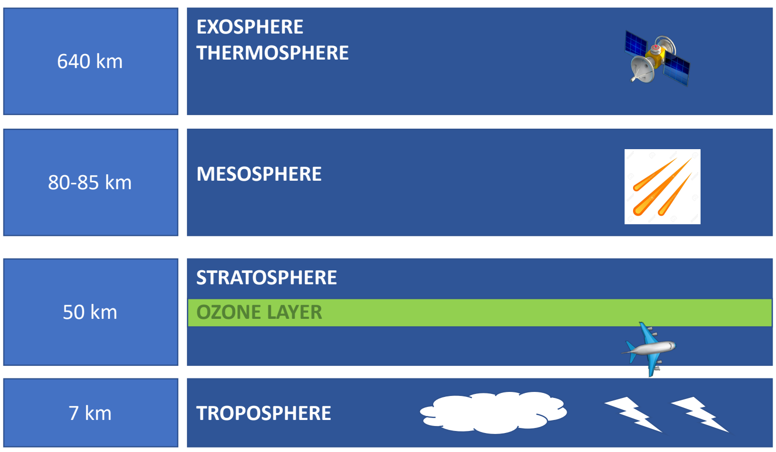


Figure 1.1.1 The regions of atmosphere

In order to determine air pollution, clean-unpolluted air in troposphere should be defined. Even though the composition of air may vary from location to location (sea, pole, desert, mountain) the dry mixture of gases is presented in table 1.1.1.

	ppm (vol.)	μg/m^3
Nitrogen	780000	8.95×10^8
Oxygen	209400	2.74×10^8
Argon	9300	1.52×10^7
Carbon dioxide	315	5.67×10^5
Neon	18	1.49×10^4
Helium	5.2	8.50×10^2
Methane	1.0-1.2	$6.56\text{-}7.87\times10^2$
Krypton	1.0	3.43×10^3
Nitrous oxide	0.5	9.00×10^2
Hydrogen	0.5	4.13×10^1
Xenon	0.08	4.29×10^2

Table 1.1. 1 The Gaseous Composition of Unpolluted Air (Dry Basis) [2]

The air also has vapor of water and organic liquids, and suspended particulate matter. After defining the clean air, air pollution can be described as harmful content in air which adversely affect human health, environmental resources and property. In United States, the Clean Air Act of 1970 determined six air pollutants; particulate matter (PM), ozone (O_3), carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen dioxide (NO_2) and lead (Pb). Environmental Protection Agency (EPA) sets the upper limits of these pollutants in air to protect public health and environment, the pollutant concentrations have to be below the limits and are used to determine the air quality.

As described previously PM is a complex mixture of liquid and solid particles of different sizes (also different composition, sources and properties) suspended in the air. The particulate amount and movement in air are dynamic, some particles act as nuclei which vapor condense around, some particles collide, adhere and fall to ground, some particles move in the air. Even though the other pollutants are described by their chemical composition, PM is described by physical size. PM10 is particulate matter 10 micrometer or less in diameter, PM2.5 is particulate matter 2.5 micrometer or less in diameter. Smaller and lighter particles are suspended in air for long periods compared to larger particles. Combustion engines, factories, burning, and mining are some of the sources of PM.

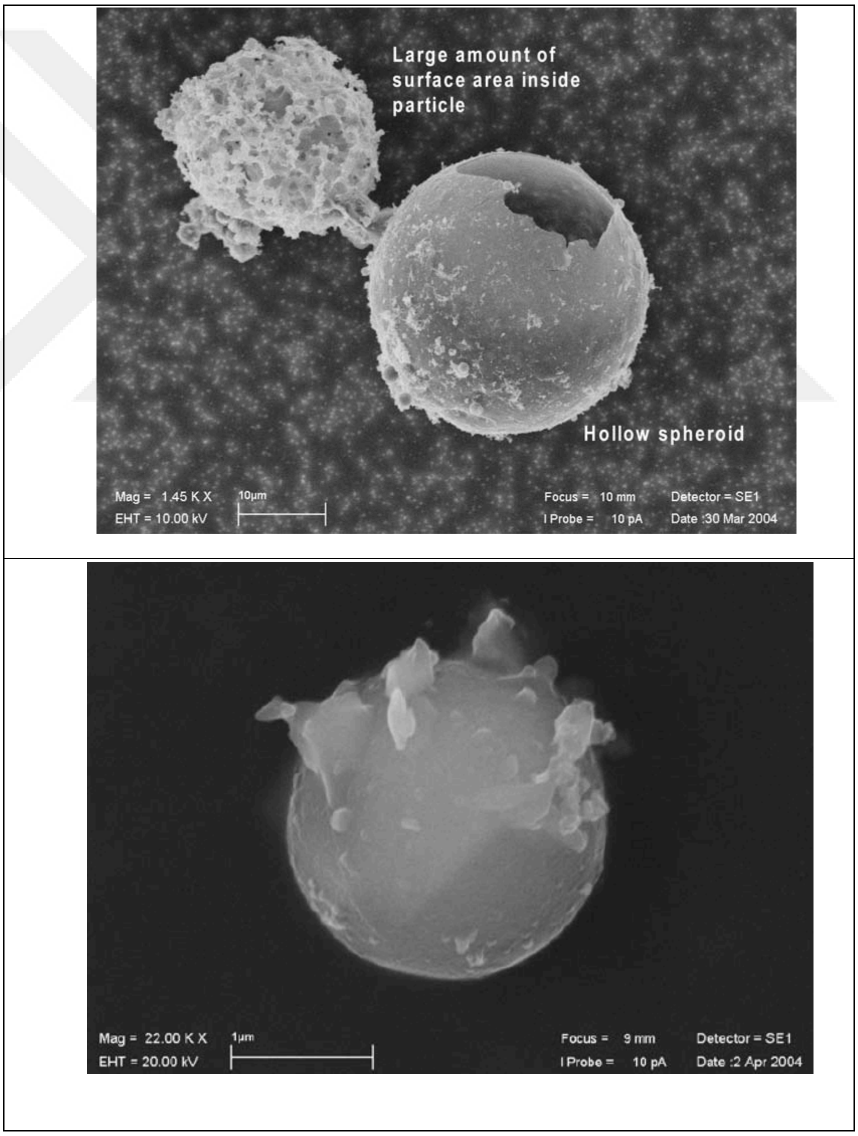


Figure 1.1.2 Scanning electron microscope images of particles from an oil-fired power plant [10].

Not all PM particles as shown in figure 1.1.2 are spherical but some particles are elongated named as fibers. One of the most dangerous PM is asbestos fibers which are toxic when inhaled [11]. The particles in air mix and travel by turbulence and wind and they can travel hundreds of miles [2]. A general representation of the air pollution generation, transportation, transformation and reaching to ground is depicted in figure 1.1.3.

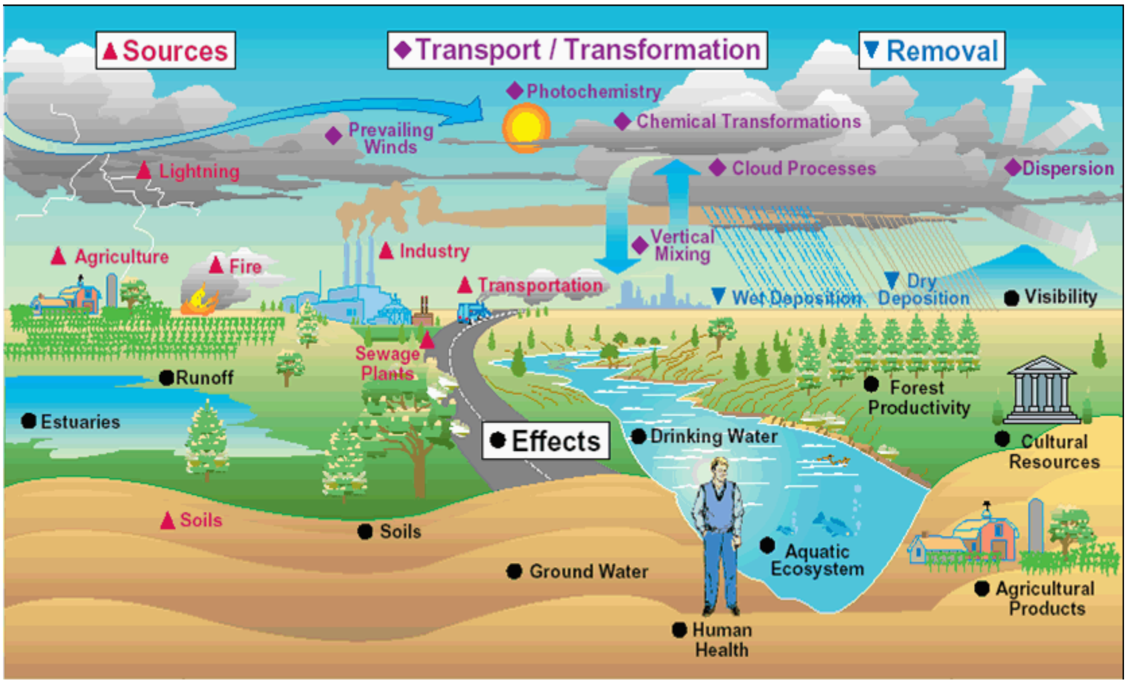


Figure 1.1.3 Global pollutant circuit [12][13]

1.2 Health Effects of PM

As described in the previous section PM is not uniform in size and composition. The health effect of PM depends on several factors such as duration of exposure, sensitivity of the individual, composition of the particles. The main entry point of PM to human body is airways (Figure 1.4). There are several filters in the airway of human body that stop the PM based on the size. For example PM>10 µm is accumulated in the extrathoracic region, PM between 5-10 µm is accumulated in the tracheobronchial region, PM<2.5 µm is accumulated in the alveolar region [14]. Accumulation degree may differ based on gender, it was reported that particles between 3-5 μm accumulated more in women compared to men [15]. People having respiratory disease are more sensitive to particles as compared to healthy individuals [16]. PM<0.1 μm is highly toxic and can penetrate to blood stream and even translocate to central nervous system which can cause destructive effects in the body [17], [18].

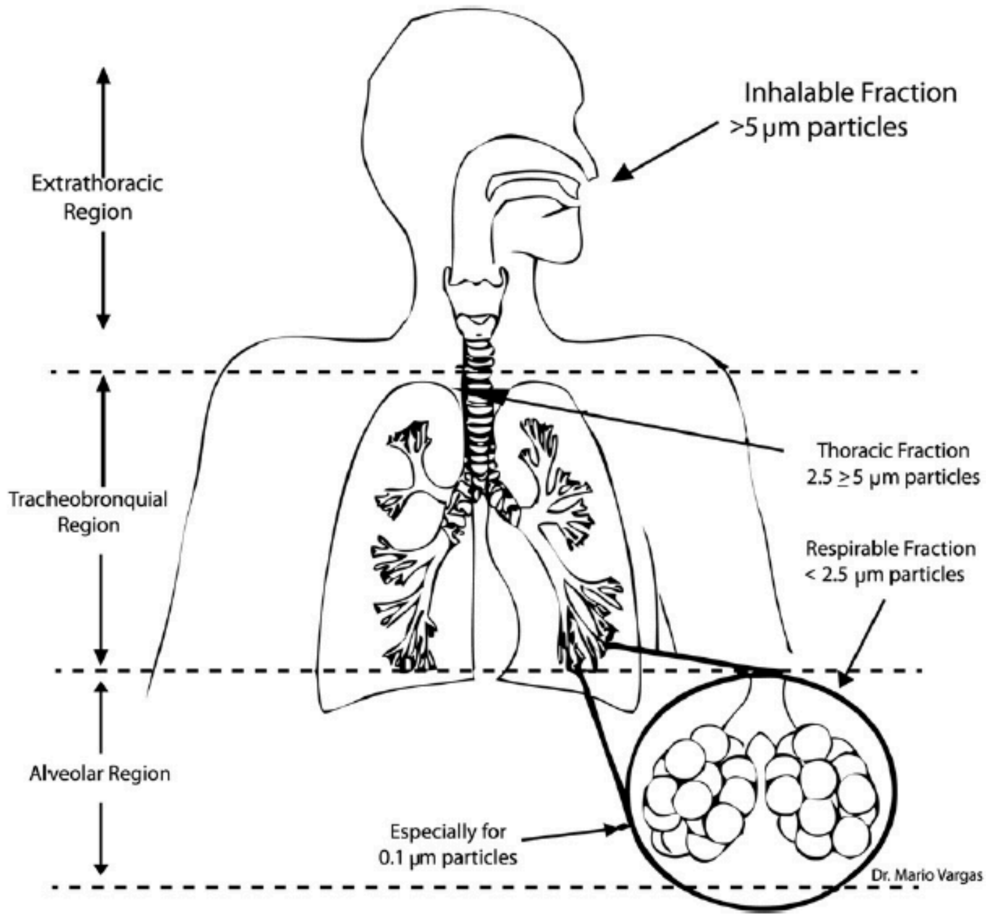


Figure 1.2.1 Airways of particle deposition in human body [14].

1.2.1 Allergic Diseases

In general, asthma is characterized by overexpression of immunoglobulin E against common allergens [19]. Experimental studies showed that diesel-exhaust particles promote immunoglobulin E production [20]. Also diesel-exhaust particles induce inflammation in healthy humans [21]. Increased levels of PM in air can cause easier penetration of pollens into the body and increase the release of antigens from pollens thus leading to hyperresponsiveness of the body [22].

1.2.2 Lung Damage

PM rich in iron, copper, zinc manganese in human body can produce reactive oxygen specifically hydroxyl and superoxide anion radicals, which can cause cellular membrane lipids and proteins [23], [24]. When free radicals increased, the intracellular Ca^{2+} concentrations elevate and induce cell damage and apoptosis [25]. It was shown that year-round exposure to particle pollution can considerably damage to the airways of the lungs [26].

There are several studies in the literature reporting the impact of PM to human and public health [27], [28]. In of those long-term studies, it was mentioned that 34000 premature deaths per year can be avoided if particle pollution was decreased by 1 $\mu g/m^3$[29]. The PM pollution is also linked to the increased risk of death from cardiovascular disease [30] and infant mortality[31].

Chapter 2

State of the art Measurement Techniques

Air pollution causes serious health and environmental problems. Continuous monitoring is required by laws and monitoring stations generally operated by governments. The conventional stations are bulky and usually 2-3 of them installed for a mid-size city (Figure 2.1). The cost of such a station is around 6000-36000 [32]. The surrounding local factors can affect the measurements of the stations thus the measurements may not represent the air quality of the area where the station is located [33].

Figure 2. 1 A conventional air quality monitoring station [34]**.**

Even though the spatial resolution of a station is poor, the measurements are accurate and can be monitored from a center. A station is equipped with different sensing equipment to monitor CO, SO_2, PM, Lead, O_3, NO levels in air.

Since there are few stations in a city, mathematical estimation models are used to monitor the air quality between the stations. However these estimations can be inaccurate [35].

2.1 Conventional Devices

Instruments based on different sensing principles have been developed to detect PM. For example, gravimetric devices have a filter to collect the particles in a steam of air flow. The filter is weighed before and after the sample collection. The particle concentration determined based on the weight change of the filter [36] . Another sensing principle is opacity where light intensity change due to absorption and scattering of light passing through a gas stream is measured. The measurement setup is depicted in figure 2.1.1.

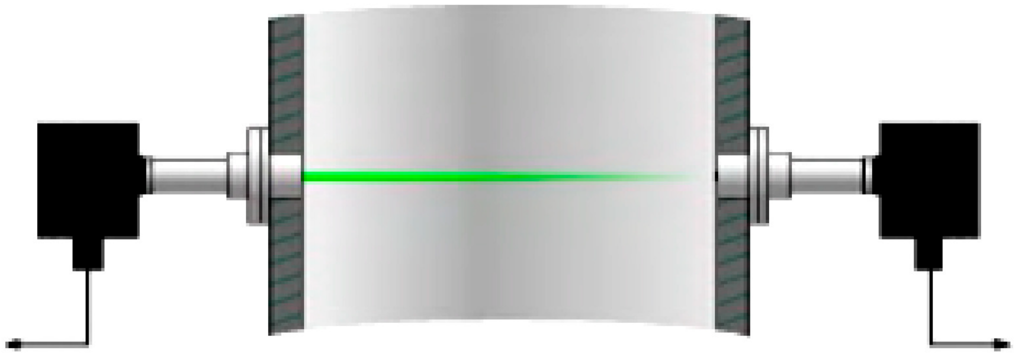


Figure 2.1.1 Opacity measurement setup [37]**.**

The receiver measures the variations of light intensity (I) which represents the amount of particulate in the gas stream. The transmittance (T) is determined by equation 2.1.1 where I_0 is reference light intensity.

$$T = \frac{I}{I_0} \quad \textbf{(2.1.1)}$$

Opacity (Op) can be derived from equation (2.1.2):

$$Op = 1 - T \quad \textbf{(2.1.2)}$$

Opacity measurements are correlated to particulate concentrations with the help of a reference system. Usually a red or near infrared light source is used for opacity measurements. Opacity based measurements are commonly used for measuring exhaust of engines [38], [39].

When light hits a particle, based on the concentration, size, shape and optical properties of the particle, the amount of scattered light would vary. There are two theories explaining scattering; Rayleigh and Mie (Figure 2.1.2). If the particles are smaller than the wavelength of the light, Rayleigh scattering occurs, and if the particle size is equal or larger than the wavelength of the incident light Mie scattering occurs.

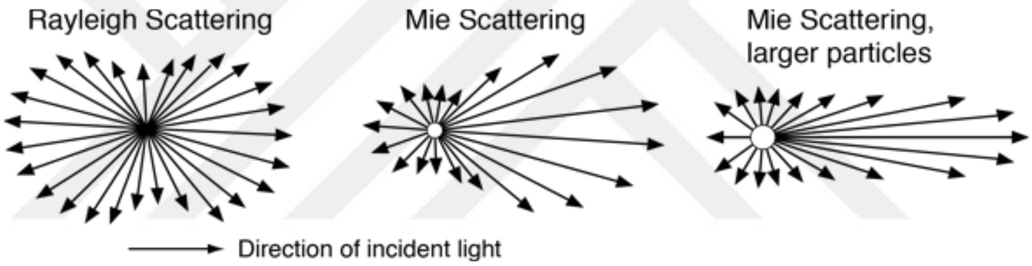


Figure 2.1.2 Rayleigh and Mie Scattering [40]

Rayleigh scattering was originally formulated to apply small spherical particles that are dielectric. Mie scattering theory has no size limitations but the formulation of the theory is complex. For that reason, usually Rayleigh theory is preferred. In Rayleigh scattering theory $x \ll 1$ and $|m|x \ll 1$, where α is the dimensionless size parameter defined as

$$x = \frac{2\pi a}{\lambda} \quad \textbf{(2.1.3)}$$

where a is the spherical particle radius, and λ is the relative scattering wavelength defined as

$$\lambda = \frac{\lambda_0}{m_0} \quad \textbf{(2.1.4)}$$

where λ_0 is the incident wavelength in vacuum, and m_0 represents the refractive index of the surrounding medium. *m*, is the complex refractive index of the scattering particle,

$$m = n - ik \quad \textbf{(2.1.5)}$$

The magnitude of the m is needed for Rayleigh criteria which corresponds to the particle is sufficiently small and has a uniform electric field [41].

The intensity of the scattered radiation for Rayleigh scattering is

$$I = I_0 \frac{(1+cos^2\theta)}{2R^2}\left(\frac{2\pi}{\lambda}\right)^4\left(\frac{n^2-1}{n^2+2}\right)^2\left(\frac{D}{2}\right)^6 \quad \textbf{(2.1.6)}$$

where n is the refractive index of the material, D is the diameter, θ is the scattering angle. Mie scattering theory is preferred when x ≈ 1. The scattering regimes for single spheres are shown in figure 2.1.3. Scattering from many non-spherical objects is complex and computer assisted calculations are needed. Mie scattering formulas are not presented in this thesis but can be found in the literature [41]

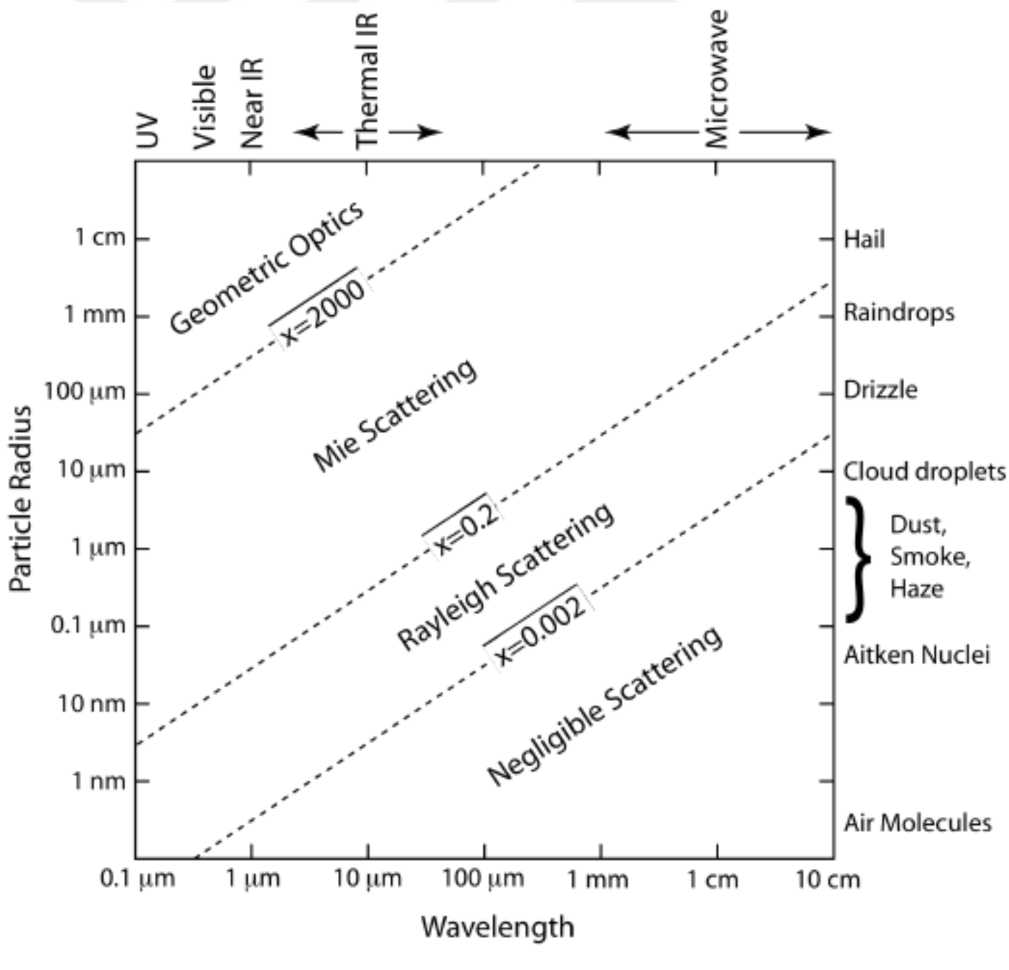


Figure 2.1. 3 Scattering Regimes [42]

Forward, side or backward scattered light can be measured using a photo detector and amount of particulate matter can be obtained. A schematic of a light-scattering setup is depicted in figure 2.1.4.

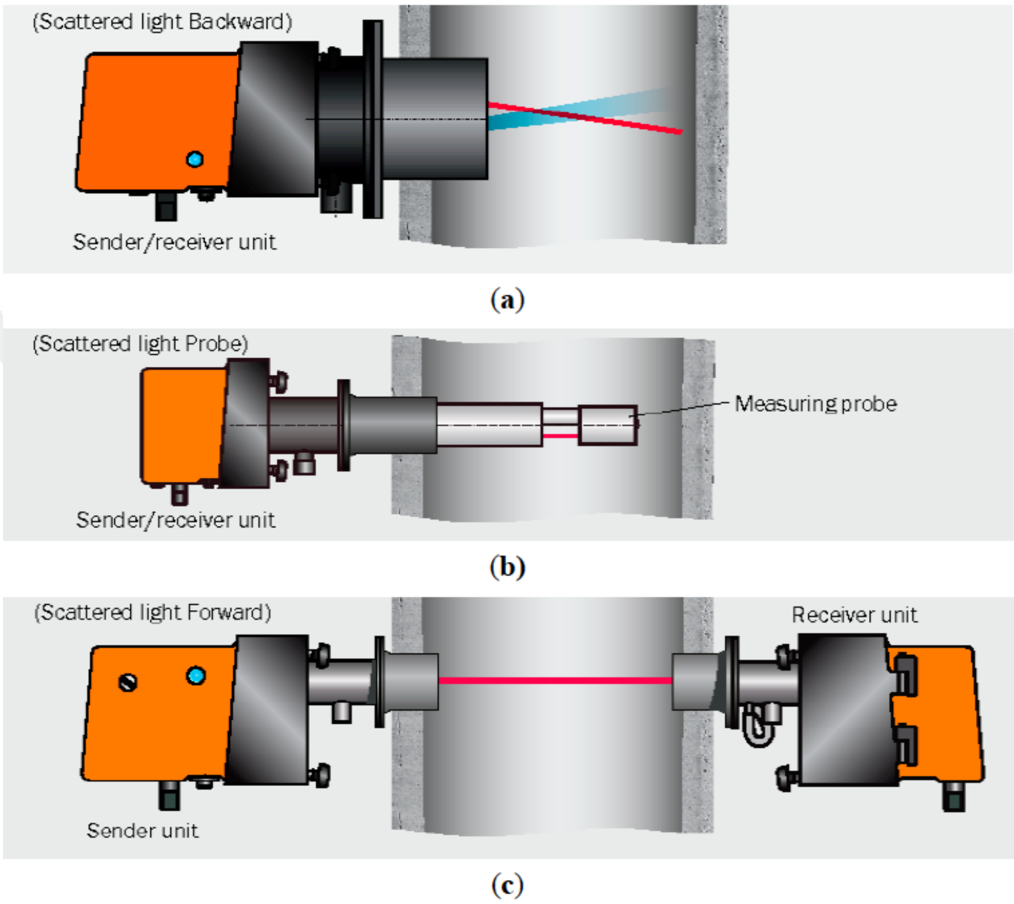


Figure 2.1.4 Light-scattering configurations a)backward b) probe forward, c) cross forward setups [43]**.**

Some of the instruments on the market based on light scattering, house a white lamp and some others house laser diode, and they provide a range of 0-200 mg/m^3 [38].

Beta Attenuation principle is also used for detecting PM (Figure 2.1.5). In this method, the air sample is drawn in a chamber and collected on a filtering band. In the system there are beta radiation sources, filter band pass through the beta ray and detectors measure the beta ray variations.

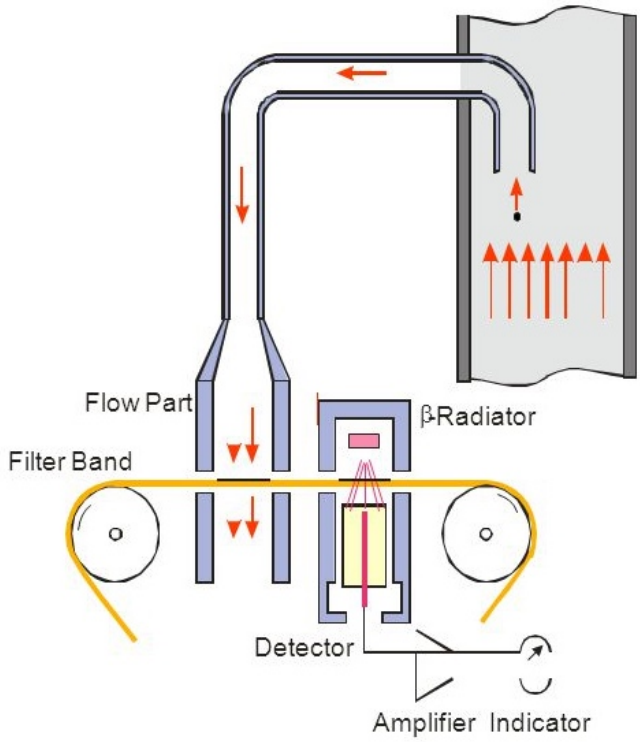


Figure 2.1.5 Beta Attenuation Measurement Technique [44].

The electron density of the target material absorbs, reflects or passes the beta rays, PM collected on filter band cause attenuation because of the absorption of beta rays and variations of the beta ray are proportional to the amount of PM.

Triboelectric effect is a type of contact electrification and can be used to measure PM. In this method when particles hit or pass close to a conductor, a charge transfer or induction occurs. The velocity, mass, and charge of the particle affects the amount of charge variation on the conductor. A schematic of the triboelectric device is shown in figure 2.1.6.

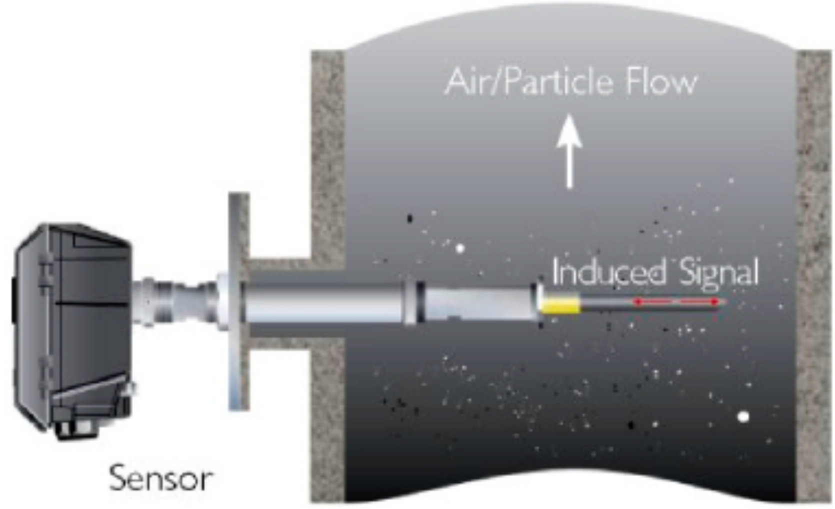


Figure 2.1.6 Triboelectric device [45]**.**

Even though triboelectric monitors are very sensitive they perform best when the particle material in non-conductive [38].

The disadvantages of the conventional methods lead researchers to explore alternative air quality monitoring systems. The advantages of new generation devices are common: 1) low-cost 2) high spatial resolution 3) small form factor. In addition to these advantages, an air quality monitoring system should provide real time, accurate and robust measurements [46]. Usually low-cost systems focus on measuring either gas or PM measurements [47]. Beyond the sensor part, other considerations of the low-cost systems that need to be carefully designed are power data management, and sensor network.

2.2 Low Cost Devices

A low cost system, HazeWatch, is reported in [48], where the system is composed of a CO sensor, a microcontroller with built-in ADC, a Bluetooth module and a battery. The measurements are transmitted to a cell phone using the Bluetooth device. Researchers also developed an app for uploading data to a database along with the GPS information. The sensor box is located on top of a car and as car traveled air quality readings performed. The cost of the sensor system is $150 excluding the cell phone. Using the uploaded data on MySQL database, and estimation models, contour map of the CO concentration was obtained. The system is tested in Sydney where 15 conventional monitoring stations are located.

A similar system which is composed of an Arduino microcontroller, a Wi-Fi module, a GPS module and a CO sensor was tested together with a prediction algorithm [49]. Another cell phone based system, GasMobile, is introduced in [50] where an Ozone sensor was connected to a cell phone through RS232-TTL interface. Ozone pollution maps were created after collecting data. A personal environmental monitoring system integrating multiple (UV, PM, Noise, Temperature and Humidity) sensors is developed (Figure 2.2.1) [51].

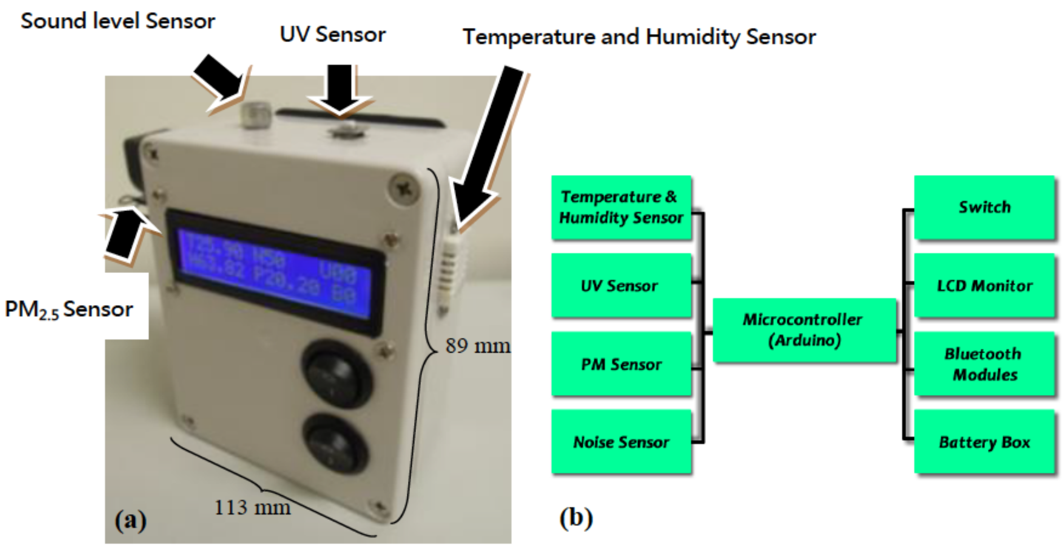


Figure 2.2.1 Integrated Environmental Monitoring Device [51].

For PM measurements, Sharp GP2Y1010AU0F dust sensor consisting of an infra-red emitting diode and a phototransistor is used in the device. The device has an Arduino microcontroller and Bluetooth module to communicate with the app on a cell phone. The data on the cell phone is transferred to a server. Both indoor and outdoor measurements performed with carrying the unit. Six AA alkaline batteries provide 30 h usage time.

2.3 Low Cost PM Sensors

Three low-cost PM sensors Shinyei (PPD42NS), Samyoung (DSM501A) and Sharp (GP2Y1010AU0F) based on light- scattering were compared previously [52]. The dimensions and working principles of these three sensors are shown in Figure 2.3.1.

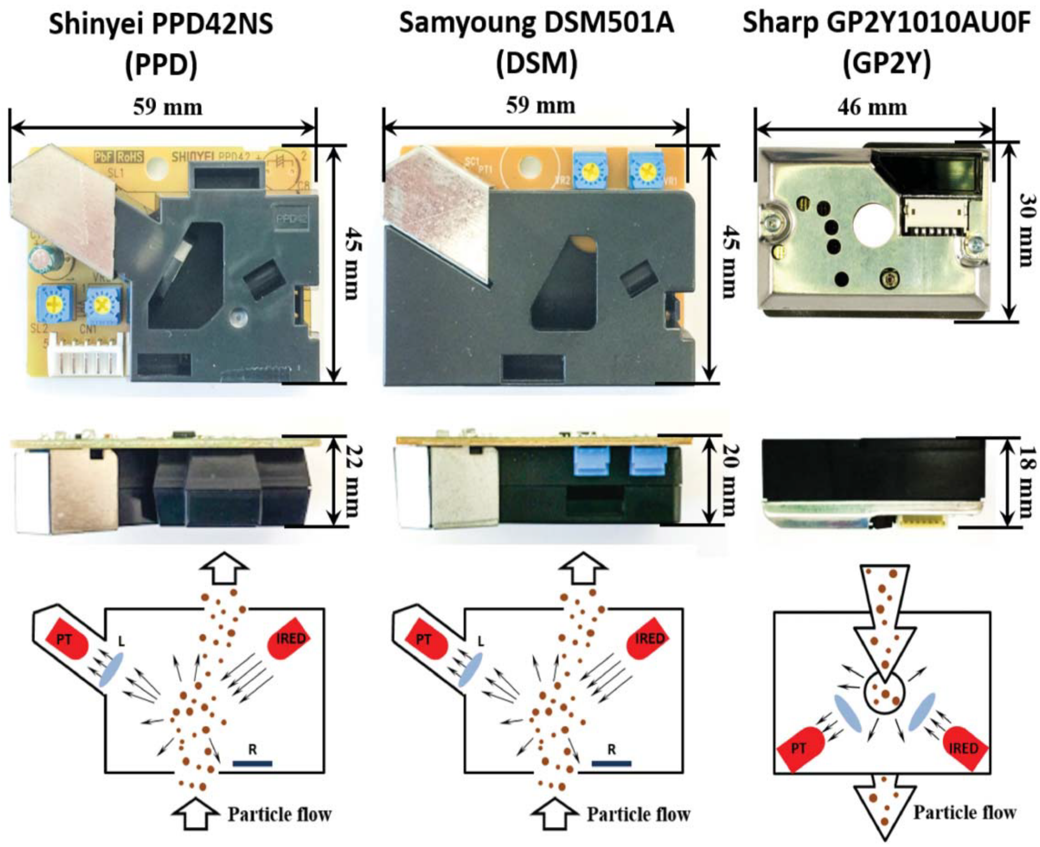


Figure 2.3.1 Three low cost PM sensors [52].

The Sharp GP2Y is smaller and cheaper ($10) than other two models. It also has lower current consumption (<20mA) and provide analog output. In order to compare three sensors a chamber was built where sensors were placed in. The particles were generated by burning incense and a reference instrument (SidePak from TSI Inc) was used. Several performance parameters such as linearity, precision, limit of detection, relative humidity and temperature influence were tested (table 2.3.1).

Parameter	Shinyei PPD	Samyoung DSM	Sharp GP2Y
Linearity of response	Medium	Low	High
Precision of measurement Accuracy	Medium	Low	High
Repeatability	Low	High	Medium
Limit of detection	Low	Low	High
Dependence on composition	High	High	High
Sensitivity to particle size	High	High	High
RH influence	High	High	High
Temperature influence	Minimal	Minimal	Minimal

Table 2.3.1 Comparison of PPD, DSM and GP2Y PM sensors [52]

The findings in table 2.3.1 suggests that Sharp GP2Y sensor demonstrates a better performance compared to other two sensors. For that reason, Sharp sensor was chosen for this study.

Chapter 3

Optical Sensor Design

As explained in the previous chapter, Sharp GP2Y sensor was chosen due to the advantages reported in the literature. Mie scattering simulations were performed to better understand the Sharp GP2Y sensor design and comparison measurements of Sharp GP2Y with a reference system (Fluke 985) were conducted. Simulation results and comparison tests revealed that modifications of the Sharp GP2Y sensor can be performed as a new sensor design and improved performance can be obtained. In this chapter, the simulation results of Mie scattering and modifications on the Sharp GP2Y sensor are introduced.

3.1 Optical Simulations

In order to analyze the Sharp GP2Y sensor, the light source of the sensor is disassembled and intensity measurements were performed using a spectrometer (Ocean Optics). The light source has a maximum peak at 930 nm and Full Width Half Maximum (FWHM) is 36 nm (Figure 3.1.1).

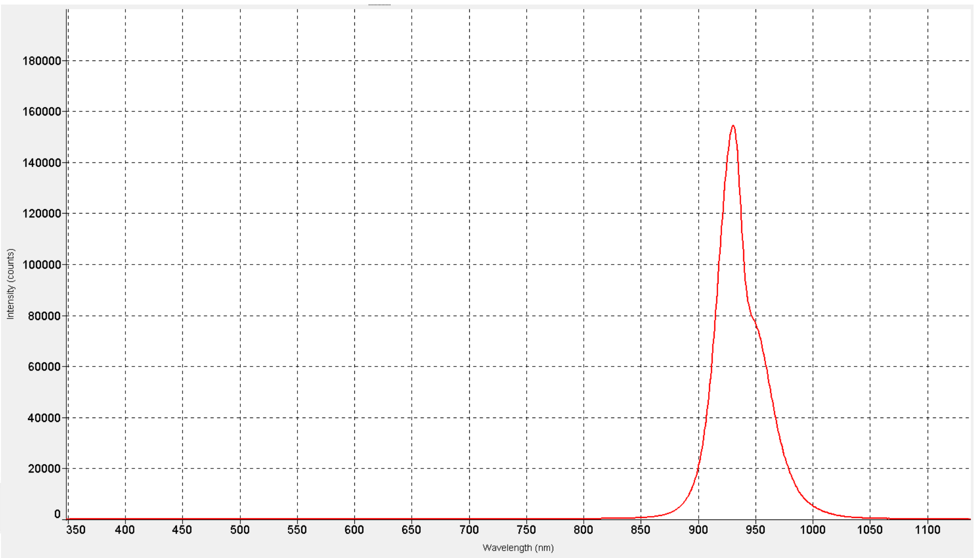


Figure 3.1.1: The measurement of the light source of the Sharp GP2Y

The online Mie Scattering calculator was prepared by Scott Prahl and is based on the Mie theory to calculate the scattering phase functions. The sphere diameter, wavelength of the incident light, refraction index, concentration of particles are the input parameters for the calculator and the scattering efficiency, the scattering coefficient, and the phase function were calculated. The refractive index of the PM 2.5 is in the range of 1.3-1.8 [53] and thus 1.5 is used in the simulations.

For a light source of 930 nm wavelength and 0.1 spheres/micron^3 the Mie scattering plot is show in figure 3.1.2.

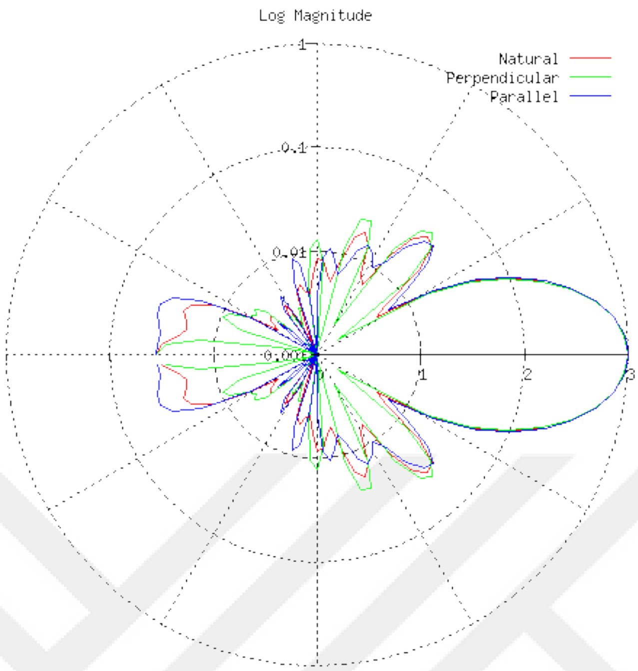


Figure 3.1.2: Mie simulation result of 1st set of parameters

By using the figure 3.1.2, the placement of the photo detector can be analyzed, where to get the maximum signal from the side lobe, the angle between the detector and the light source should be between 120-150 degrees. The Sharp GP2Y has a 120 degree between the light source and the photo detector. The simulation graph shows a symmetrical response and if the signal needs to be increased a second photo detector can be added to the sensor system. It is also possible to place a second photo detector to detect lower scattered signals and thus increase the dynamic range of the existing sensor which has single photo detector.

By using a 3D printer several housing samples which enable assembling a light source and two photo detectors with related circuitry at desired angles were produced (figure 3.1.3). The original Sharp GP2Y sensor and the modified sensors were compared with the reference system Fluke 985.

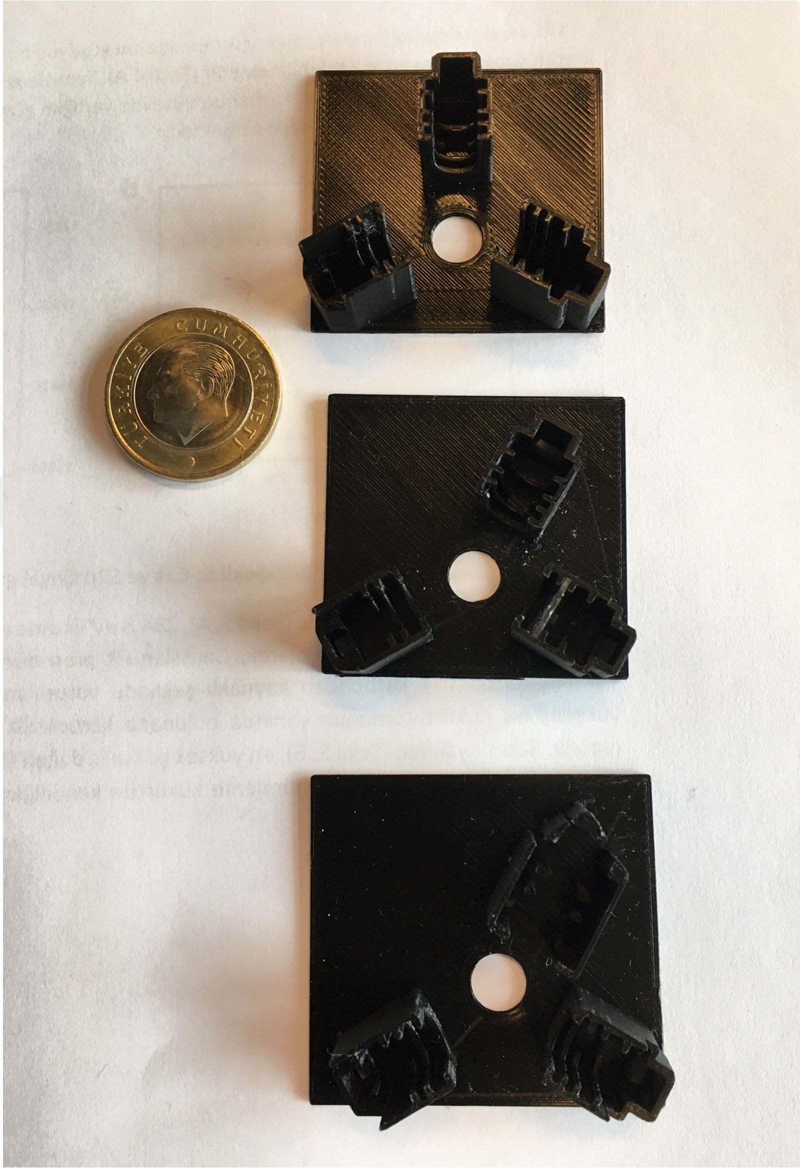


Figure 3.1.3 3D printed housings for different prototypes of the sensors.

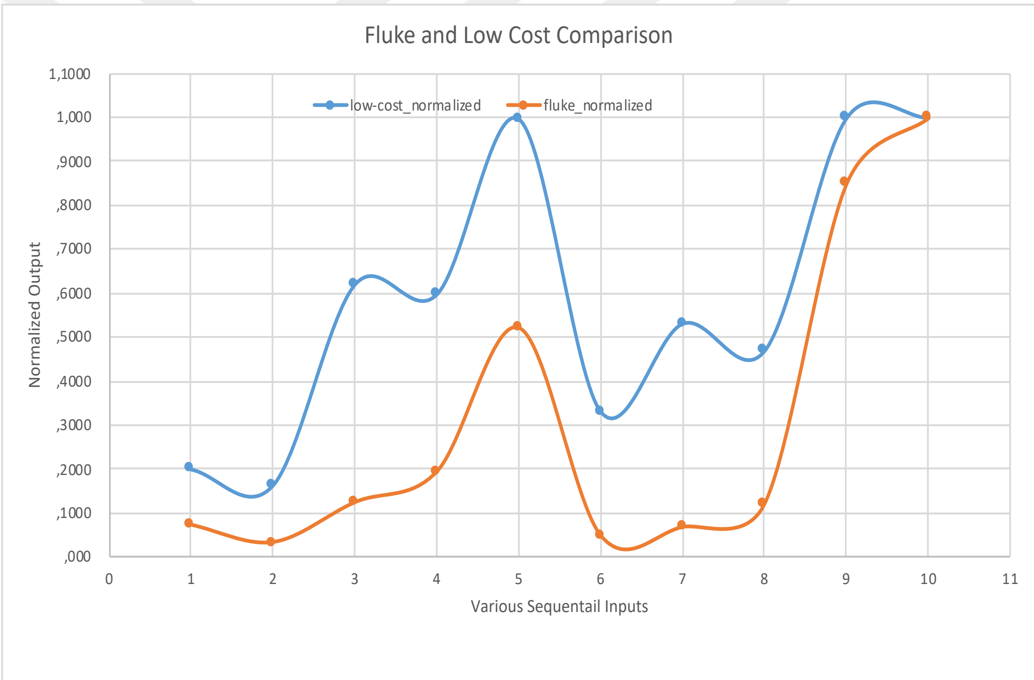
3.2 Comparison Measurements

In the literature a simple candle smoke test was reported to test the PM measurement devices [54]. Using a similar approach, we used a soldering station and solder paste to create PM. We measured the PM in air using the reference instrument and various sensor designs and compared the outputs.

3.2.1 Sharp GP2Y versus Fluke

Since Sharp GP2Y was chosen as the base platform and further modifications will be made on it, comparison experiments should be performed. We used solder paste experiment to create PM and measured the PM amount using Fluke and Sharp GP2Y simultaneously. We changed the amount of solder paste sequentially and recorded the changes of both sensors. We normalized the results to compare the outputs (Figure 3.2.1.1).

A



B

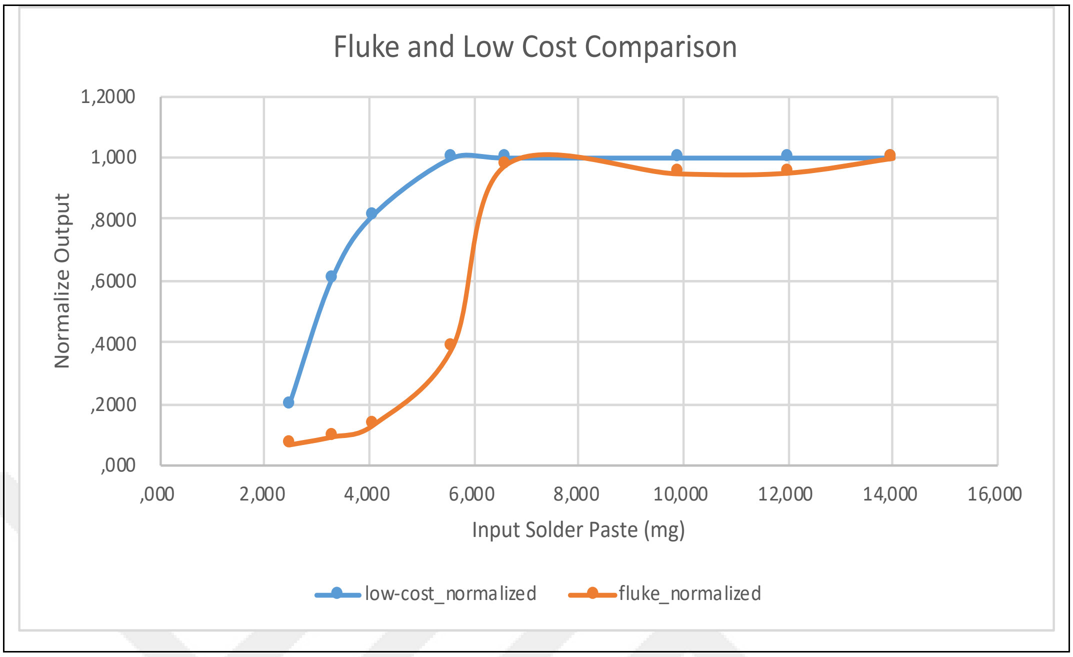


Figure 3.2.1.1 The comparison of Fluke and Low-Cost Sensor A: Sequential Random Input B: Determined Input.

These results revealed that low-cost sensor measures the PM with and acceptable error and trends of both high-cost and low-cost are very similar. By performing these experiments, we tested the performance of the low-cost sensor and we are convinced to build the prototypes on the low-cost sensor platform.

3.2.2 Optical Sensor Prototype 1

In the original Sharp GP2Y sensor, there is 120^0 between the light source and the photo detector. To test the impact of a second photo detector at 90^0, we designed our prototype 1 with two detectors; one at 120^0 and the second one at 90^0 as shown in figure 3.2.2.1.

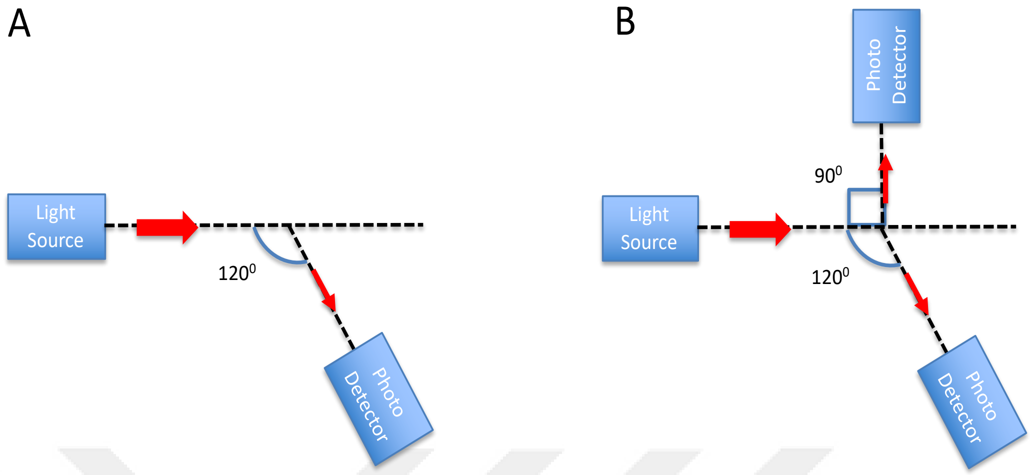
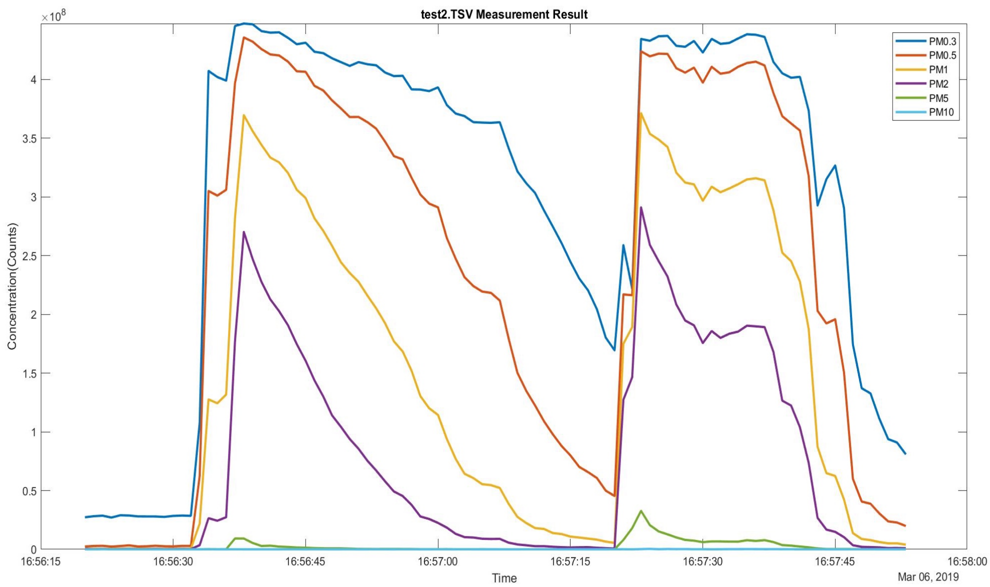


Figure 3.2.2.1 Orientation of the light source and the photo detectors A) The design of Sharp GP2Y, B) The design of prototype 1.

We used solder paste to create the input signal and measured the PM simultaneously with the reference system (Fluke), Sharp GP2Y and prototype 1 (figure 3.2.2.2).

A



B

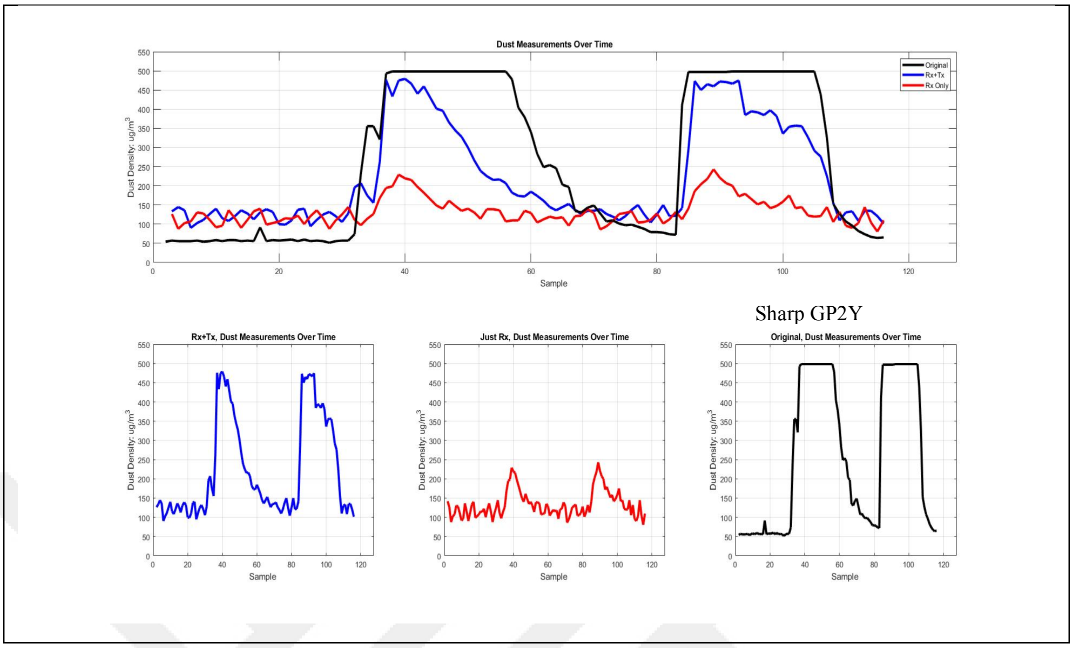


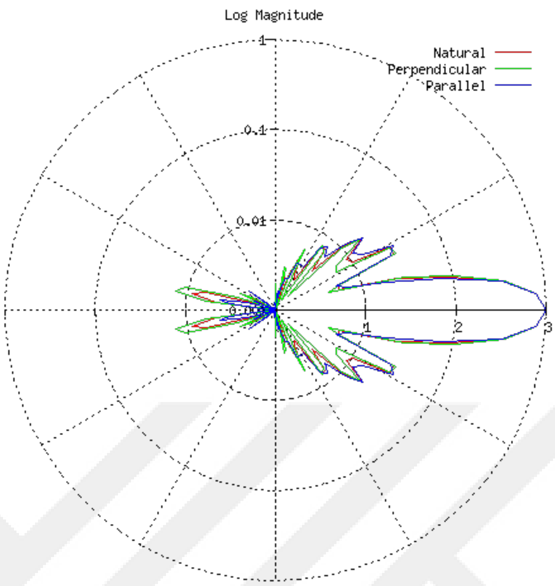
Figure 3.2.2.2 The comparison of outputs of Fluke, Sharp GP2Y and prototype 1. A) Fluke output for six PM values, B) Top: Sharp GP2Y and prototype 1 together, Bottom: Individual graphs (blue: prototype 1, 120^0), (red: prototype 1, 90^0), (black: Sharp GP2Y 120^0).

The measurements in figure 3.2.2.2 reveal that prototype 1 has higher noise compared to Sharp GP2Y however, it did not reach to saturation as Sharp GP2Y did. The photodetector located at 90^0 provided lower signal as expected. The outputs of the low cost sensors (Sharp GP2Y and prototype 1) and the output of the reference system (Fluke) have a similar trend but the values from low cost sensors need a conversion factor.

3.2.3 The effect of light source

One of the design parameters is the wavelength of the light source. We also performed simulations to analyze the impact of the wavelength (Figure 3.2.2.3). However not all light sources in the desired form factors are offered on the market, so we decided to use the 935 nm as it is readily available. In the future work we can explore the new designs including shorter wavelength light sources.

A)



B)

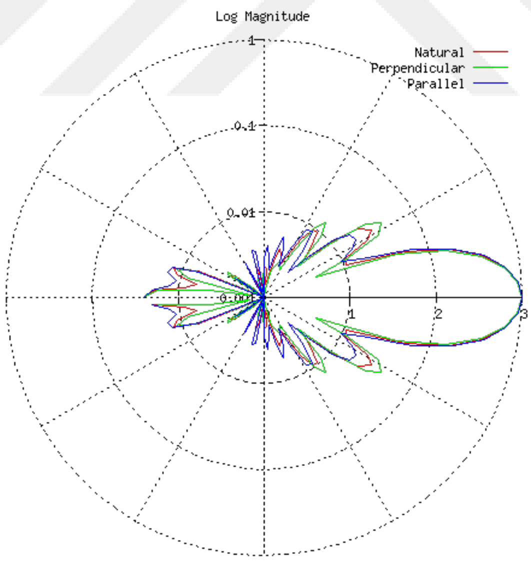


Figure 3.2.2.3 The impact of the wavelength of the incident light A) 400 nm B) 600 nm

3.3.4 Optical Sensor Prototype 2 and 3

We also performed measurements for the designs where the second photodetectors are located at 120^0 and 150^0. These locations caused saturation and did not improve the sensor performance (Figure 3.3.4.1).

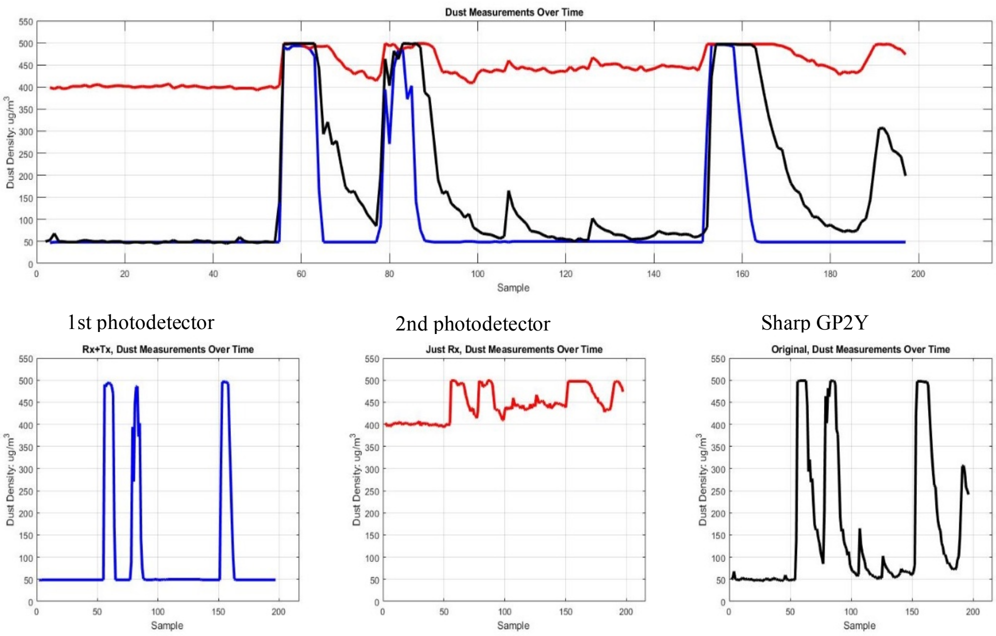


Figure 3.3.4.1 The outputs of Sharp GP2Y and prototype 2.

The red graph in the figure 3.3.4.1 is the output of the second photodetector which was located at 120^0. A similar output was obtained from the photodetector located at 150^0. Because of the poor performance of the second photodetector, prototype 1 was preferred for the sensor box.

Chapter 4

Software Development

Cloud Computing has various advantages for sensor networks such as providing high computation power, network integration and data analysis. Companies like Amazon, Microsoft and Google offer cloud computing services [55]. Amazon Web Services (AWS) provide Elastic Computing Cloud (EC2) for dynamic computing needs, and Simple Storage Service (S3) for extensible storage space which make it attractive for sensor network applications [56]. For the aforementioned reasons we used AWS for our cloud computing needs. There are mainly four communication protocols used in IoT applications [57]:

1) Message Queuing Telemetry Transport (MQTT)
2) Constrained Application Protocol (CoAP)
3) Advanced Message Queuing Protocol (AMQP)
4) Hyper-Text Transfer Protocol (HTTP)

MQTT is one of the oldest machine-to-machine communication protocol and designed for basic messaging and enables only few control options. By using MQTT, messages are transferred to certain topics and clients can receive the messages if they subscribed to the topic. Instead of topics, CoAP is based on Universal Resource Identifier (URI) for machine-to-machine communication where data is send to URI and then all subscribers are notified, CoAP provides more functionality compared to MQTT [58]. AMQP communication is based on creating “exchanges” between publishers and clients. HTTP also uses URI and globally accepted web messaging standard. The comparison of four protocols is summarized in table 4.1.

Criteria	MQTT	CoAP	AMQP	HTTP
Published in	1999	2010	2003	1997
Architecture	Client/Broker	Client/Server or Client/Broker	Client/Server or Client/Broker	Client/Server
Abstraction	Publish/ Subscribe	Request/ Response or Publish/ Subscribe	Request/Response or Publish/Subscribe	Request/Response
Header Size	2 Byte	4 Byte	8 Byte	Undefined
Message Size	<256 MB	Fit in single IP datagram	Negotiable	Large
Semantics / Methods	Connect, Disconnect, Publish, Subscribe, Unsubscribe, Close	Get, Post, Put, Delete	Consume, Deliver, Publish, Get, Select, Ack, Delete, Nack, Recover, Reject, Open, Close	Get, Post, Head, Put, Patch, Options, Connect, Delete
Cache and Proxy Support	Partial	Yes	Yes	Yes
Quality of Service (QoS) /Reliability	QoS 0- at most once, QoS 1- at least once, QoS 2-exactly once	Confirmable message	Settle Format or Unsettle Format	Limited (via Transport Protocol)
Standards	OASIS, Eclipse Foundations	IETF, Eclipse Foundation	OASIS, ISO/IEC	IETF and W3C
Transport Protocol	TCP (also UDP)	UDP, SCTP	TCP, SCTP	TCP
Security	TLS/SSL	DTLS, IPSec	TLS/SSL, IPSec, SASL	TLS/SSL
Default Port	1883/883 (TLS/SSL)	5683 (UDP Port) / 5684 (DLTS)	5671 (TLS/SSL)	80/443 (TLS/SSL)
Encoding Format	Binary	Binary	Binary	Text
Licensing	Open Source	Open Source	Open Source	Free
Support	IBM, Facebook, Cisco, AWS	Cisco, Contiki	Microsoft, JP Morgan	Global Web Protocol

Table 4. 1 Comparison of MQTT, CoAP, AMQP and HTTP [57]

Each protocol has advantages and disadvantage, for example HTTP is the global web protocol and has the highest message size and overhead compared to other methods. On the other hand, CoAP has the lowest power consumption and resource requirements [57]. The decision of which protocol to use depends on the user requirements and accessibility. In our case we would like to have a web-based user interface so HTTP protocol is more suitable for our application.

4.1 Codes on Sensor Box and on Amazon Cloud Computing

The cloud computing system is depicted in figure 4.1.1. The sensor box has SIM 808 GSM and GPRS module with the communication antenna. The microcontroller (Arduino) runs attention (AT) commands to establish the communication between the SIM 808 module and the HTTP server.

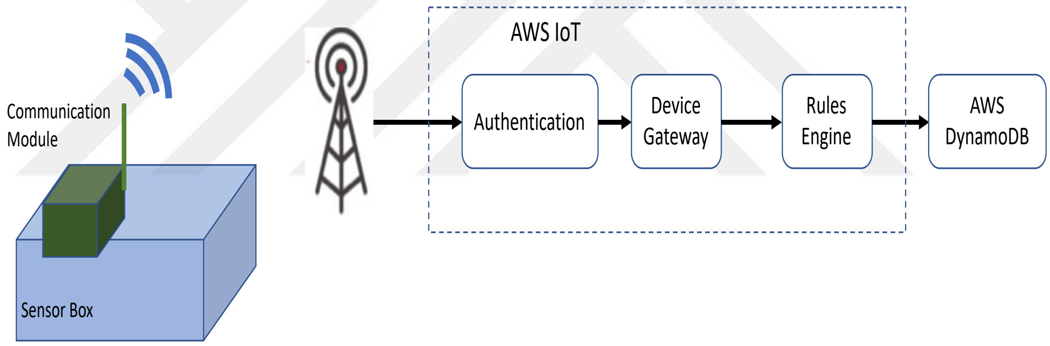


Figure 4.1.1 Block Diagram of the Established Cloud Computing System

The communication process between the sensor box and the cloud computing:

1) SIM 808 module sets GPRS connection through the sim card 2G data service
2) Microcontroller gets GPS location info (via AT Commands) from SIM 808 module
3) Microcontroller establishes HTTP connection (via AT Commands) to AWS API Gateway
4) Microcontroller sends GPS location data and sensor data through HTTP connection.

5) Data is captured by AWS Lambda (Rules Engine) and inserted into AWS DynamoDB.

In this project we used both Arduino Uno and Nano as the microcontroller. There are two main functions run on the microcontroller Setup and Loop (Figure 4.1.2).

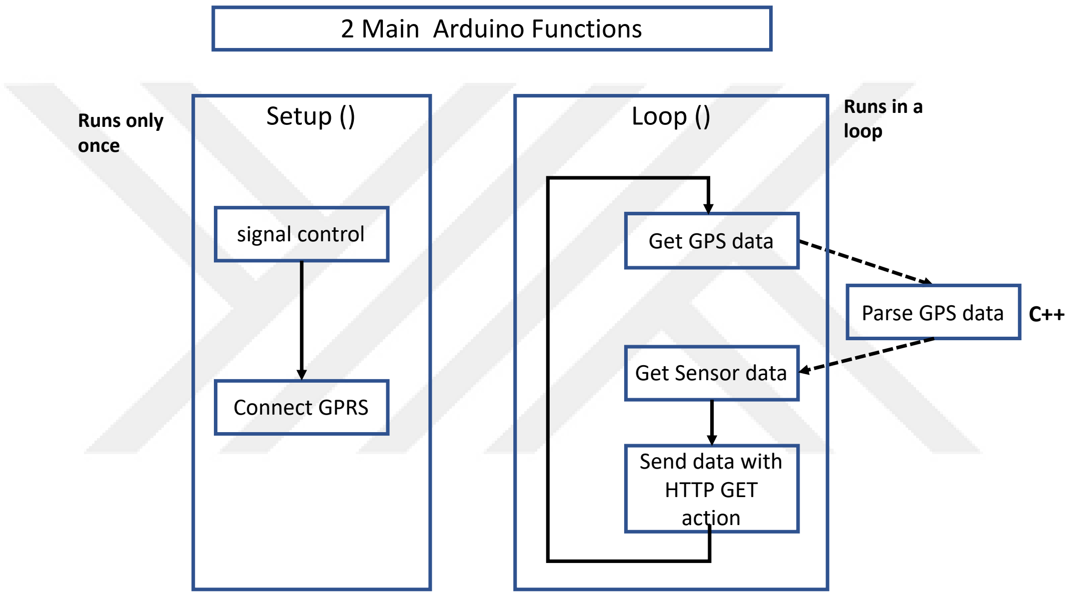


Figure 4.1.2 The Main Arduino functions

These two functions establish the connection to SIM 808 communication module and command for the HTTP connection. The GPS data is parsed in C++ and send back to Arduino for further processing.

On the SIM 808 communication module, AT Commands run as shown in table 4.1.1.

Check sigral	AT+CSQ
Connect GPRS	1) AT+SAPBR=3,1, “GONTYPE”, “GPRS” 2) AT+SAPBR=3,1, “APN”, “internet” 3) AT+SAPBR=0,1 4) AT+SAPBR=1,1 5) AT+SAPBR=2,1

Get GPS data	1) AT+CGNSPWR=1 2) AT+CGPSINF returns:<mode>, <UTC time>, <longitude>, <latitude>, <altitude>, <TTFF> *(time to first fix)*, <num>, <spread>, <course>
Send data with HTTP get action	1) AT+HTTPINIT (*Initialize HTTP connection*) 2) AT+HTTPSSL=1 (Enable SSL) *3)* AT+HTTPPARA= "CID", 1 *(set HTTP parameter)* 4) AT+HTTPPARA= "URL", "….amazon.com" 5) AT+HTTPACTION=0 *(set HTTP Action as GET)* 6) AT+HTTPREAD *(Read Server Response)* 7) AT+HTTPTERM *(Terminate HTTP Service)*

Table 4.1.1 AT Commands for SIM 808

The developed software shown in figure 4.1.2 and table 4.1.1 run on the hardware of the sensor box. The next step is to communicate with the cloud computing and run developed codes on the AWS (Figure 4.1.3). Sensor box (Arduino and SIM 808 module) generates HTTP requests which are sent to API Gateway. On AWS Lambda user-defined codes (functions) run as AWS Lambda supports Java, Python, and Node.js. In this project Node.js.8.10 codes developed and run on AWS Lambda. Amazon DynamoDB is a NoSQL database service to create database tables to store sensor data. In our project we have Sensor data as the combination of time and payload. Time column includes Coordinated Universal Time (UTC), and Payload includes latitude, longitude and Particulate Matter (PM) data. Once the data is received on AWS DynamoDB it can be further processed using other platforms such as Java or Python.

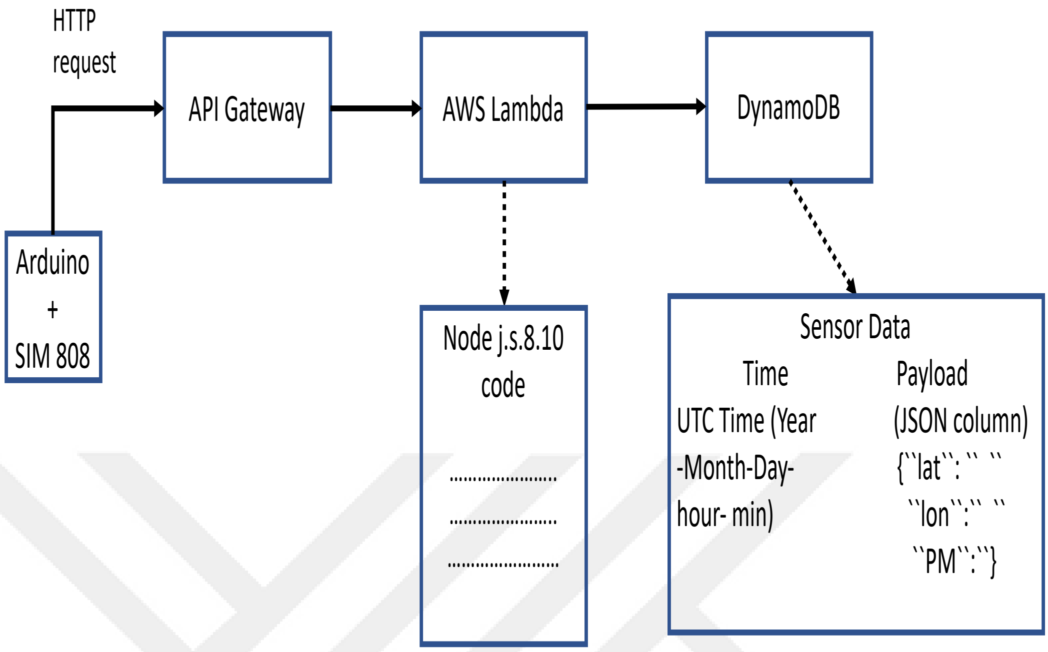


Figure 4.1. 3 Software codes on AWS

4.2 Measurements

The modules of the sensor box are shown in figure 4.2.1. The GSM/GPS module, optical sensor, microcontroller, battery and antennas are the hardware modules.

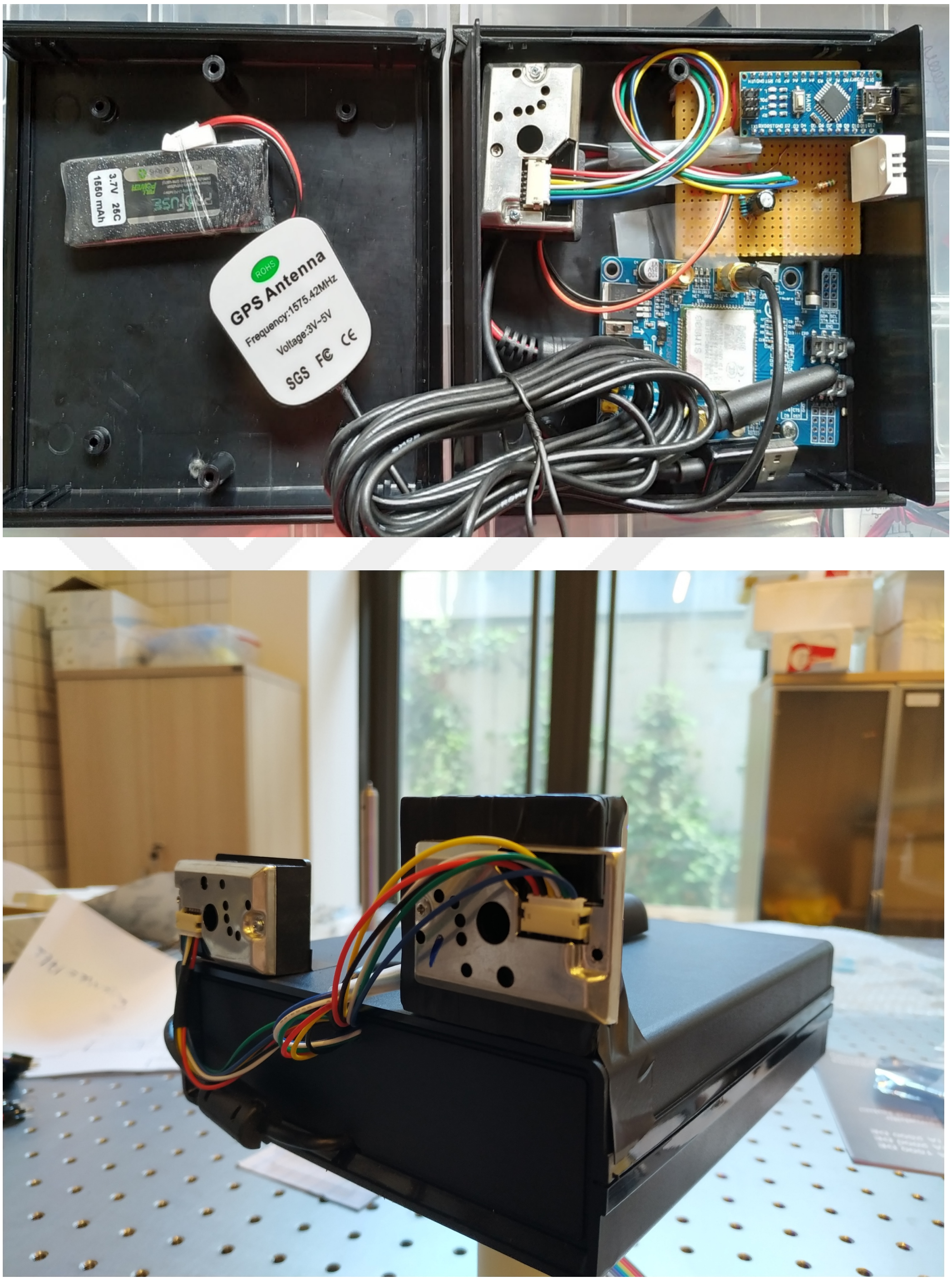


Figure 4.2.1 The sensor box inside and closed box.

Many sensor boxes will form the sensor network, and thus collecting data from many different locations will be available.

After producing the sensor box and establishing the cloud computing structure, we performed measurements at different locations and compared the results with the reference system (Fluke). The first comparison was car exhaust measurement where the low-cost sensor and the fluke were placed close to a car's exhaust as shown in the figure. The gas pedal pushed two times and released to idle condition and measurements were recorded for both systems.

Figure 4.2. 2 Car exhaust measurements.

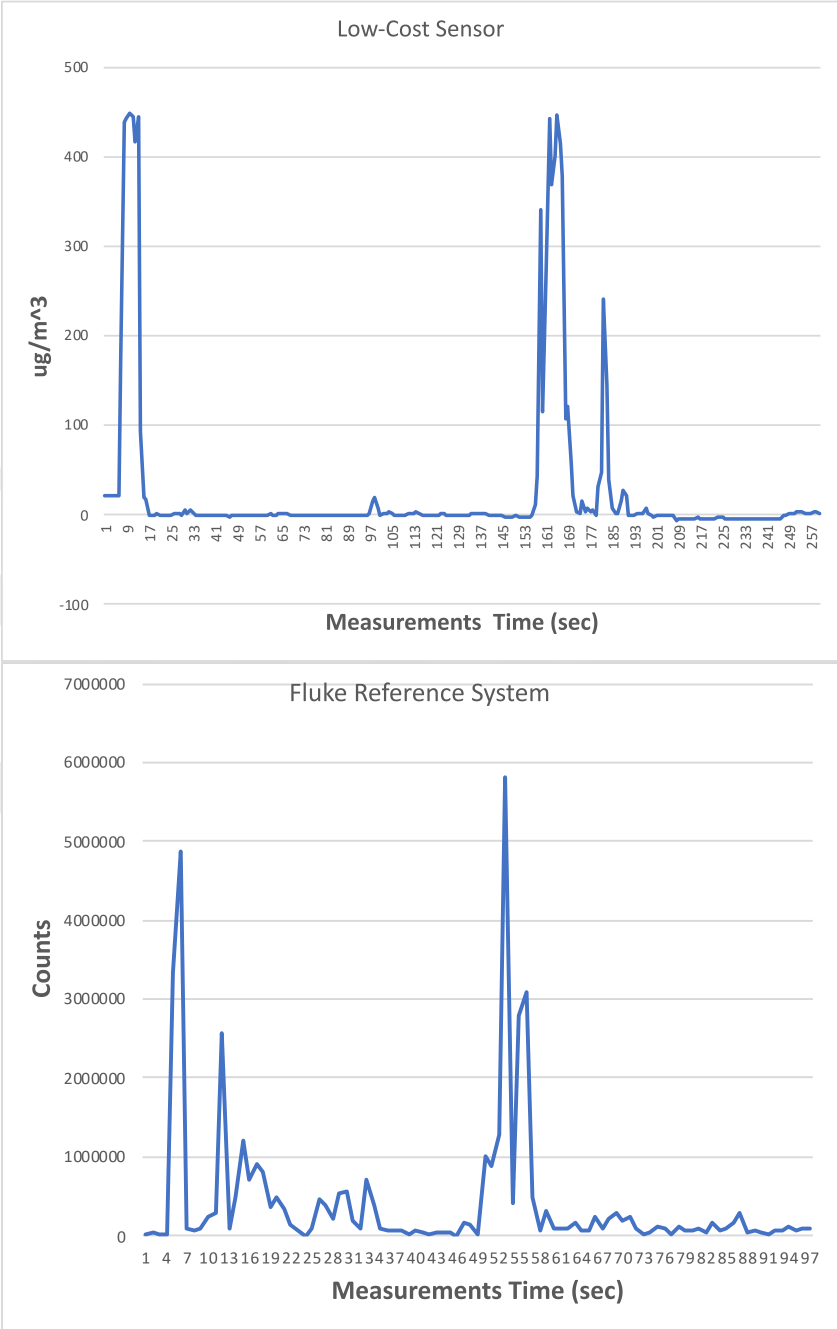


Figure 4.2. 3 The outputs of the developed system and the fluke.

The responses of the both sensor systems to gases from the car exhaust are very similar. The next measurement was performed at the traffic lights where many cars stopped when the red light is on.

Figure 4.2. 4 Traffic light measurements, outputs of the developed system and the reference.

When many cars stopped at the traffic light, placed on the sidewalk both systems can detect the increase in the PM levels. After the cars moved away and by the help of the wind the PM values returned to lower values. We also placed our system close to an air quality monitoring station in Hürriyet, Kayseri.

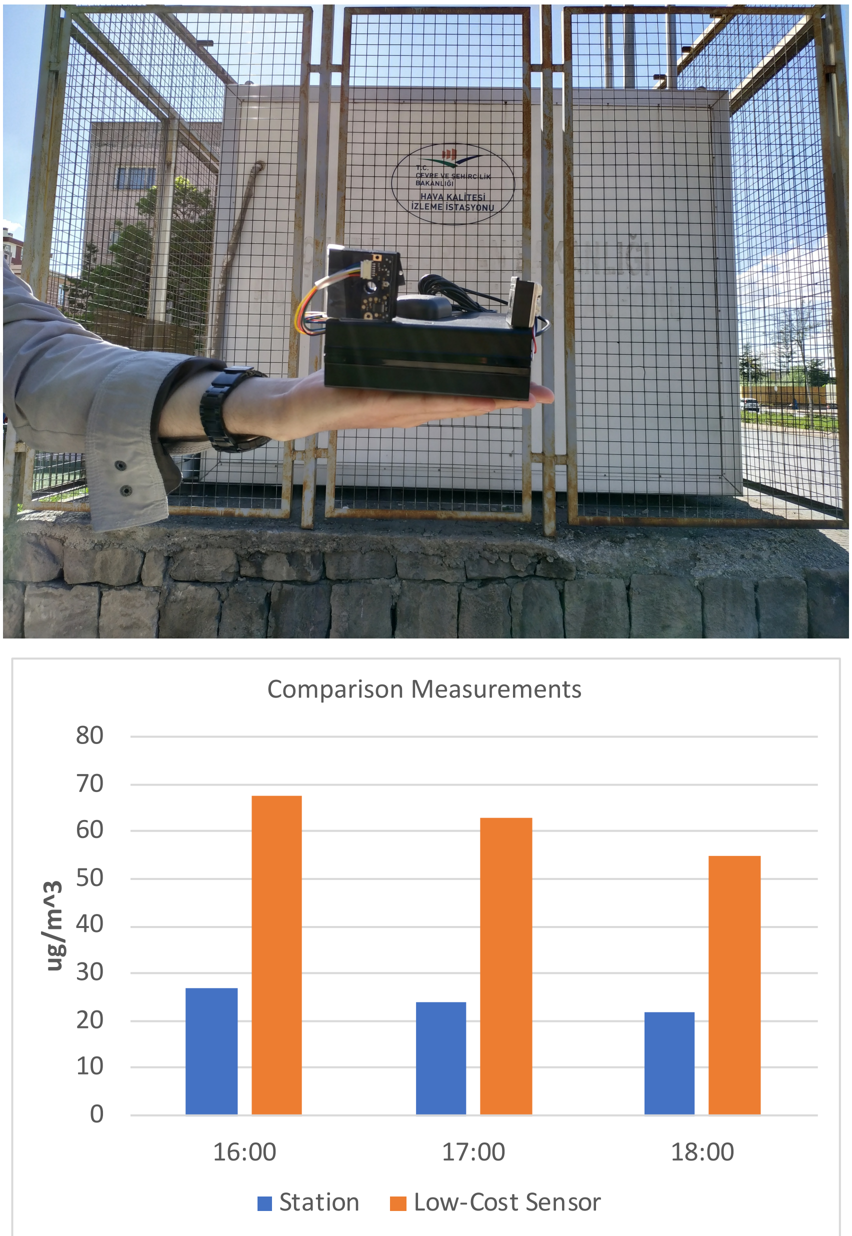


Figure 4.2. 5 Comparison with the conventional station and the outputs of both systems

The output of the station is available on the webpage (www.havaizleme.gov.tr) As seen from the figure the measurements of the station and the low-cost system are in correlation and they have a similar trend. The low-cost sensor measures higher than the station and it might be fixed easily with calibration.

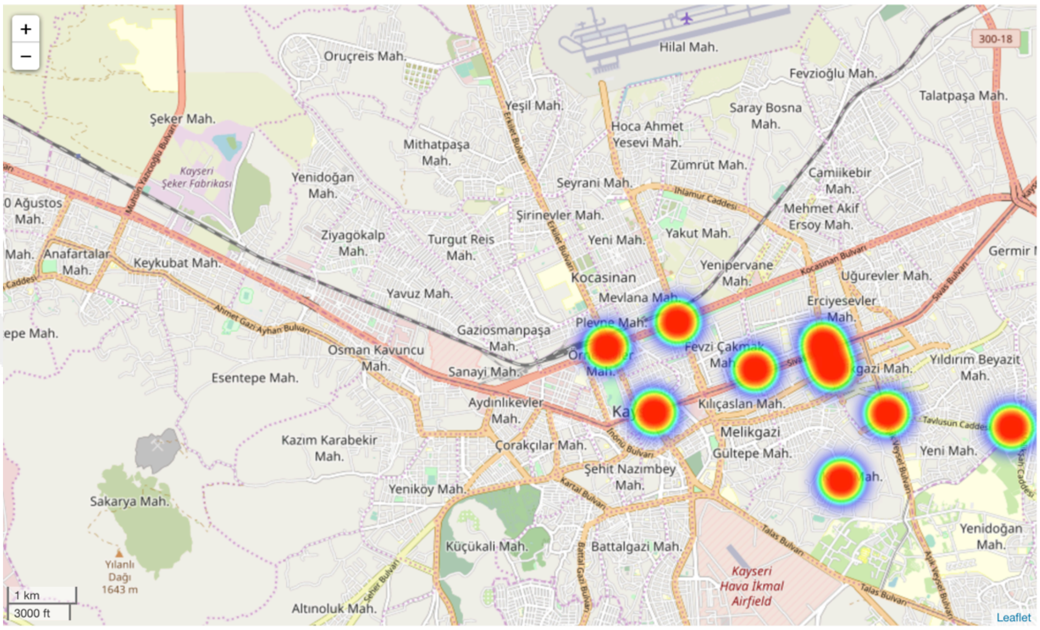


Figure 4.2.6 The heat map

In figure 4.2.6 a heat map showing the sensor output and the location of the sensor box on city map of Kayseri. The data on the AWS data base was processed using Python. Another visualization of data is using color circle map as shown in figure 4.2.7. In this representation each color of the circles represents the output of the sensor.

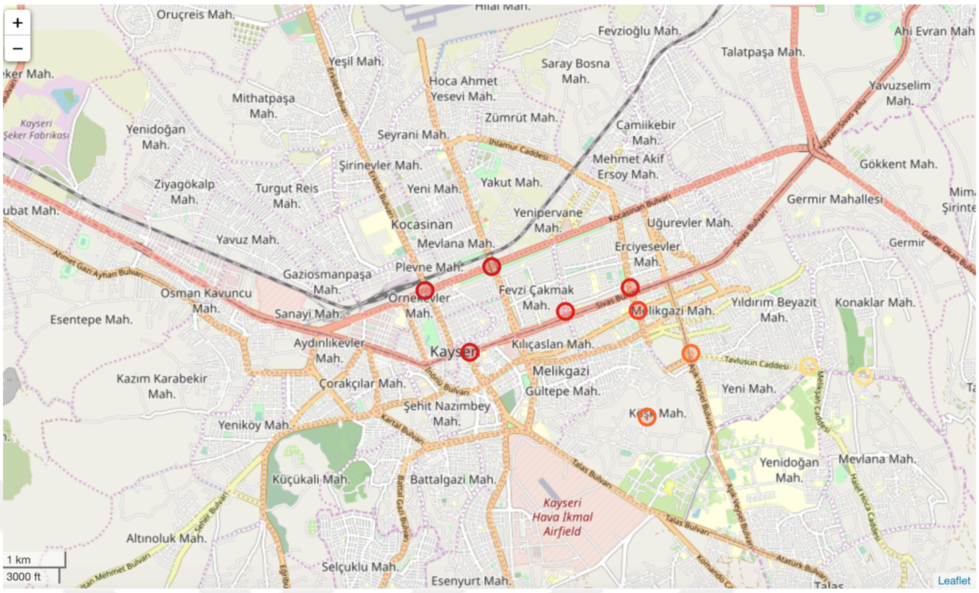


Figure 4.2.7 The color map

The third visualization of the data is marker map where both colors and clicking enabled so that user can observe the sensor output value by clicking on the markers (figure 4.2.8).

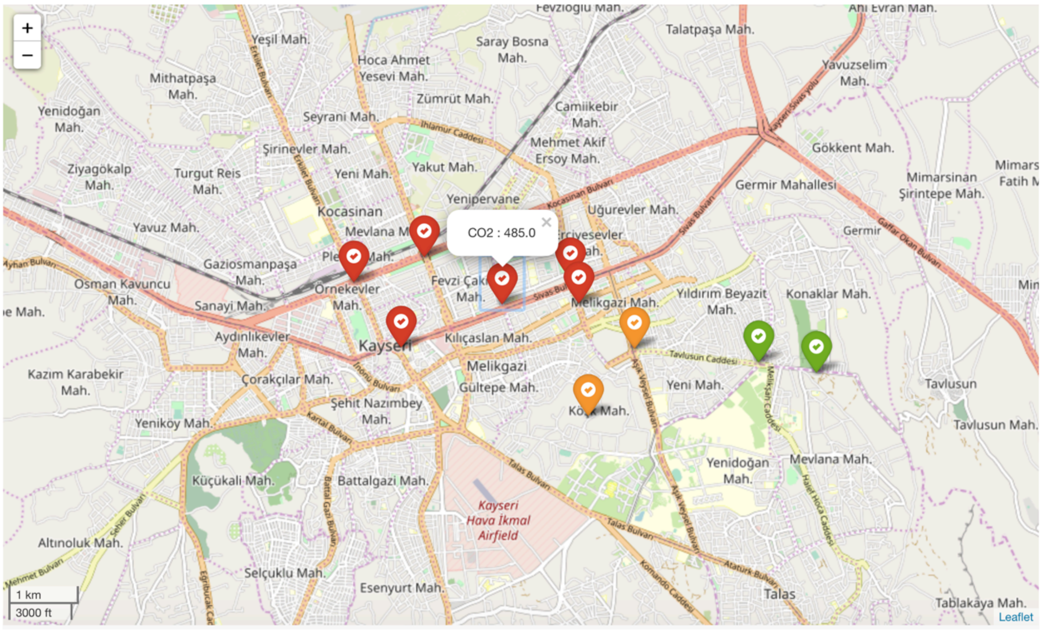


Figure 4.2.8 Marker map.

To perform full test of the system the sensor box was turned on and carried around while walking in the streets. As shown in figure 4.2.9, the collected data was sent to the server and visualized real time on the computer screen.

Figure 4.2. 9 Real time full system test: data collection while moving

To validate the performance of the sensor box, the comparison measurements between the sensor box and the fluke were performed (Figure 4.2.10). The trend line shows R^2 value of 0,9269 which is acceptable and indicates the correlation.

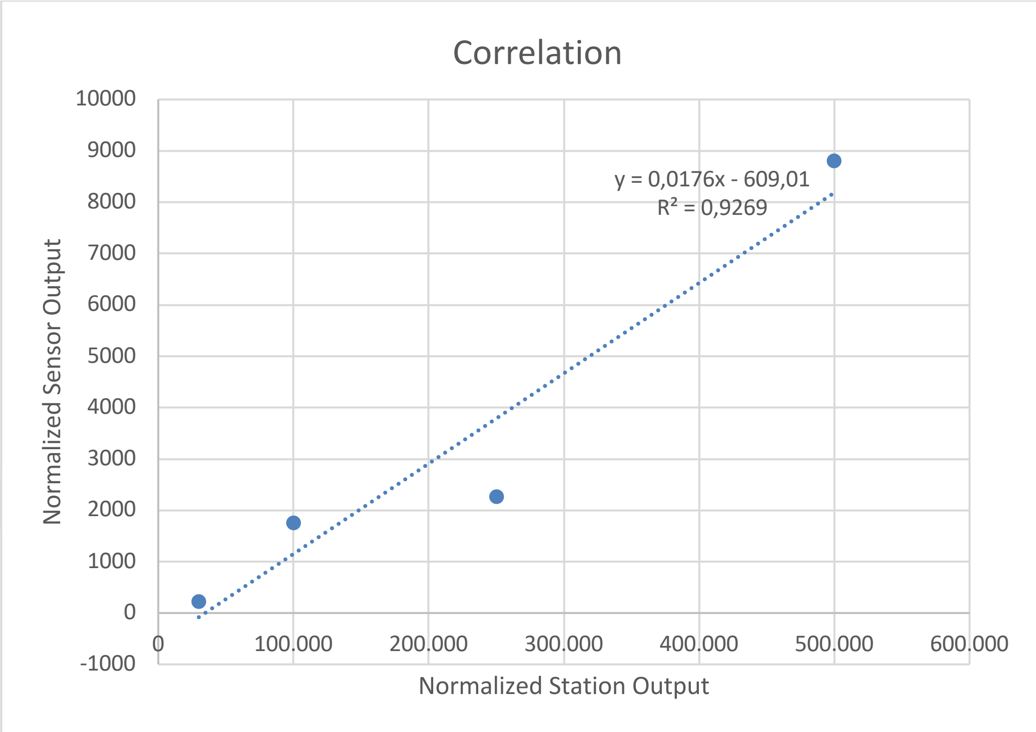


Figure 4.2. 10 Correlation measurements

The measurements reveal that low-cost sensor can be alternative to bulky and expensive stations. Also, the spatial resolution is increased by forming a sensor network.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

Air quality is utmost importance for human life. The cities with high population are facing with a serious problem of low air quality. Monitoring the air quality is mandatory by regulations. Currently bulky and expensive monitoring stations are installed in the cities. These stations only provide local measurements which does not have any value for people 1-2 km away from the station. The city of Kayseri currently has 3 stations which is not enough for a population of 1.5 million people. In Finland, a network of smaller monitoring units is integrated with the existing stations to increase the spatial resolution. The advancements in IoT and Cloud Computing lead the current trend which is low-cost sensor networks for environmental monitoring. As an alternative to the conventional air quality monitoring stations, we developed a sensor box including an optical particle sensor, a microcontroller, and a communication module. The optical particle sensor is the developed version of the Sharp dust sensor where we increased the dynamic range by adding a photodetector and the circuit at 90^0. Thus, the designed optical sensor has two photodetectors and when the initial photodetector is saturated, the second one provides data.

The other part of the project is the software portion where a database on Amazon Web Service was built. HTTP protocol was used to establish the communication between the sensor box and the AWS. SIM 808 GPS/GPRS module was preferred on the sensor box for communication. This module can transmit data at locations where cell phone reception is valid.

In this research, both hardware and software components were developed for the sensor box. After the development of the system, measurements at various locations were performed and the performance of the sensor box was compared with the stations. The correlation is acceptable and sensor box is an alternative to the existing expensive stations.

5.2 Future Work

We will continue working on developing both the hardware and the software of the sensor box. For our prototyping we used easily accessible Arduino microcontroller and SIM 808 GPS/GPRS module. We would like to try other microcontrollers and communication modules together with necessary communication protocols in a longer run. We would like to compare the impact of hardware and software improvements on the system performance. After the comparison we would like to optimize the sensor box and the communication protocol. We are also planning to implement the system using different environmental sensors. IoT has various applications and we will try to collaborate with smart sustainable city designers to integrate our systems to the current sensor network. With the new design we would like to reach real-time, reliable data with reduced cost sensor networks. To sell the electronic products in Turkey and in EU, the electronic device needs necessary certifications. In the future, we also plan to get necessary certifications for our system. Such certifications include laser safety, communication module antenna safety and electromagnetic compatibility.

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