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Σχεδιασμός και Ανάπτυξη Εφαρμογής IoT για την Παρακολούθηση Δεικτών της Ποιότητας του Αέρα

Διπλωματική Εργασία

Σάμιος Δημήτριος

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Design and Development of an IoT Application for Monitoring Air Quality Indicators

Diploma Thesis

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Περίληψη

Η ανθρώπινη υγεία και ευεξία επηρεάζεται σημαντικά από την ποιότητα του εσωτερικού αέρα, ιδιαίτερα λαμβάνοντας υπόψη τον μεγάλο χρόνο που περνούν οι άνθρωποι σε εσωτερικούς χώρους. Μέσα σε αυτό το πλαίσιο, η παρούσα διπλωματική εργασία προσφέρει μια λύση: την ανάπτυξη και εφαρμογή ενός χαμηλού κόστους συστήματος παρακολούθησης της ποιότητας του αέρα, βασισμένο στην τεχνολογία του Διαδικτύου των Πραγμάτων (IoT). Αυτό το σύστημα είναι κατασκευασμένο γύρω από τον μικροελεγκτή ESP32 και ενσωματώνει αισθητήρες για τη μέτρηση της θερμοκρασίας, της υγρασίας, του μονοξειδίου του άνθρακα, των πτητικών οργανικών ενώσεων και των σωματιδίων. Διαθέτει επίσης μια ενσωματωμένη εφαρμογή ιστού, που επιτρέπει στους χρήστες να παρακολουθούν και να αναλύουν την ποιότητα του αέρα σε πραγματικό χρόνο, ενώ ταυτόχρονα αποστέλλει δεδομένα σε μια υπηρεσία αποθήκευσης στο νέφος για περαιτέρω ανάλυση. Η ανάπτυξη του λογισμικού πραγματοποιήθηκε με τη χρήση του Arduino, της πλατφόρμας προγραμματισμού PlatformIO, και το σύστημα αρχείων SPIFFS χρησιμοποιήθηκε για την αποθήκευση των αρχείων διαμόρφωσης. Η εφαρμογή ιστού, από την άλλη πλευρά, κατασκευάστηκε χρησιμοποιώντας HTML, CSS και JavaScript. Η εφαρμογή του συστήματος δοκιμάστηκε σε ποικίλους εσωτερικούς χώρους, όπως σπίτια και γραφεία, με πολύ ενθαρρυντικά αποτελέσματα. Σύμφωνα με τα δεδομένα που συλλέχθηκαν, υπάρχουν αισθητές διακυμάνσεις στην ποιότητα του εσωτερικού αέρα, καθώς επηρεάζονται από παράγοντες όπως η εξαερισμός, η ανθρώπινη δραστηριότητα και η παρουσία διαφόρων πηγών ρύπων. Παρά τα ενθαρρυντικά αποτελέσματα, το σύστημα έχει ορισμένους περιορισμούς, συμπεριλαμβανομένης της απαίτησης βαθμονόμησης των αισθητήρων και της δυσκολίας στην ακριβή ανίχνευση γεγονότων ρύπανσης. Για το μέλλον, η έρευνα θα πρέπει να επικεντρωθεί στην εξεύρεση λύσεων για αυτούς τους περιορισμούς, καθώς και στην επέκταση των λειτουργιών του συστήματος, συμπεριλαμβανομένης της ενσωμάτωσης επιπλέον αισθητήρων, της ενσωμάτωσης μηχανισμών ανατροφοδότησης από τους χρήστες και της βελτίωσης του υλικού και του λογισμικού. Γενικά, η διπλωματική δείχνει τη δυναμική των οικονομικά προσιτών λύσεων για την παρακολούθηση της ποιότητας του αέρα σε εσωτερικούς χώρους, καθώς και για

την προώθηση ενός πιο υγιούς περιβάλλοντος διαβίωσης και εργασίας μέσω του Διαδικτύου των Πραγμάτων.

Λέξεις-κλειδιά:
ESP32, Arduino, Ιστοσελίδα, Συλλογή δεδομένων, Ποιότητα εσωτερικού αέρα, Σωματίδια, Θερμοκρασία, Υγρασία, Τεχνολογία IoT, Οικονομικό σύστημα παρακολούθησης, Πλατφόρμα νέφους

Diploma Thesis

Design and Development of an IoT Application for Monitoring Air Quality Indicators

Samios Dimitrios

Abstract

Indoor air quality has a significant impact on human health and well-being, especially given the significant amount of time that people spend indoors. This thesis focuses on the development and implementation of a low-cost Internet of Things (IoT)-based air quality monitoring system for indoor environments. This system is based on an ESP32 microcontroller programmed using the Arduino framework and PlatformIO. It integrates sensors to measure temperature, humidity, carbon monoxide, volatile organic compounds, and particulate matter (PM2.5 and PM10). Furthermore, the system includes a web application, hosted on the IoT device, that displays the collected data and allows users to monitor and analyze air quality in real time. Data is also periodically uploaded to a cloud storage service for more detailed analysis and long-term preservation. An overview of software design and implementation, including the process of programming Arduino devices using the Arduino framework and PlatformIO, is provided in the thesis. It further explores how the SPIFFS file system stores configuration files. The web application, built with Vue.js, Bootstrap, and the Vite builder, ensures a user-friendly experience with interactive capabilities, responsive design, and optimal performance. Testing of the system took place in a variety of indoor environments, including residential and commercial spaces. According to the data collected, there are noticeable variations in indoor air quality, as influenced by factors such as ventilation, human activity, and the presence of pollutant sources. Therefore, the system is capable of monitoring these variations effectively and providing visualizations of key air quality indicators in real time. The thesis concludes by emphasizing the importance of proactive monitoring of air quality in order to mitigate potential health risks. In spite of the promising results, the system has a number of limitations, including the requirement of calibration of sensors and the difficulty in identifying pollution events precisely. Further research is suggested, including integrating additional sensors, incorporating user feedback mechanisms, and improving hardware and software. In general, the thesis demonstrates the potential of cost-effective solutions for enhancing indoor air quality as well as fostering a healthier living and working environment through the use of IoT-based air quality monitoring.

Keywords:

ESP32, Arduino, Web application, Data collection, Indoor Air Quality, Particulate Matter, Temperature, Humidity, IoT technology, Low-cost monitoring system, Cloud platform

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Abbreviations

IAP	Indoor Air Pollution
IAQ	Indoor Air Quality
SBS	Sick Building Syndrome
IoT	Internet of Things
EPA	U.S. Environmental Protection Agency
PM	Particulate Matter
BMS	Building Management Systems
HVAC	Heating, Ventilation, and Air Conditioning
CO2	Carbon Dioxide
VOC	Volatile Organic Compounds

Chapter 1 Introduction

Air pollution is a major global concern that impacts human health and contributes to climate change. As reported by the World Health Organization (WHO) [1], 4.2 million premature deaths occur every year due to exposure to air pollution. However, indoor air pollution is less discussed but due to latest studies on human exposure to indoor pollution, released by the European Commission at its Joint Research Centre (JRC) facilities in Ispra (Italy) [2], reveal that indoor environments pose their own threats to health and, in some cases, can be at least twice as polluting as outdoor environments. Given that 90% of European people [3] nowadays spend a substantial amount of their time indoors, ensuring the control of the air quality they inhale becomes an imperative requirement for enhancing their living standards.

Indoor air quality can be influenced by a range of pollutants such as Volatile Organic Compounds (VOCs), particulate matter, and carbon dioxide, among others. These pollutants can originate from various sources like cooking, cleaning products, furniture, and even outdoor air infiltrating into the building. Despite the importance of this issue, monitoring indoor air quality remains a challenge due to the lack of efficient, accessible, and affordable technology.

In recent years, the rapid development of Internet of Things (IoT) technologies have opened up new possibilities for cost-effective monitoring of environmental parameters, enabling continuous and reliable assessment. Despite these advancements, the high cost of sensors remains a major challenge when monitoring a significant number of pollutants. Consequently, achieving a comprehensive understanding of air quality often becomes impractical and expensive, particularly when a large number of sensors is required.

Among the crucial pollutants, airborne particles present a significant challenge due to the high costs associated with acquiring and maintaining appropriate measurement devices. As a result, the accurate measurement of particulate matter is often overlooked in existing monitoring systems, limiting our ability to obtain a comprehensive view of air quality.

1.1 Purpose of the Study

To address these challenges, the primary objective of this study is to design and develop a low-cost Internet of Things (IoT) application specifically tailored for monitoring indoor air quality. The system was developed with scalability in mind, utilizing IoT technologies for data gathering, local processing, and internet transmission. It will be a physical device equipped with multiple sensors and an Arduino microcontroller, allowing for the measurement of major indoor air pollutants. The collected readings will be made available in real-time via a web application, enabling users to monitor and understand the quality of the air in their indoor environments.

1.2 Overview of Remaining Chapters

The next chapter provides an overview of the relevant background information related to indoor air quality, including an explanation of the major indoor air pollutants, their sources, health impacts, and current monitoring techniques. Additionally, it examines the role of the Internet of Things (IoT) in the monitoring of air quality by providing a comprehensive overview of previous studies, benefits, challenges, and existing IoT solutions.

In the third chapter, the methodology of this study is discussed. An in-depth analysis of the system architecture, including hardware and software development, is provided in the analysis, which explains how the system functions. This section describes the hardware configuration, web interface, communication protocol, and data storage system of the IoT device. Furthermore, it discusses the device's sensors, processor, and peripheral devices, as well as the software development process.

The fourth chapter discusses the findings of the data collected with the IoT device and analyzes the results in various indoor environments, including residential and office settings. This section describes the findings and proposes possible causes and implications.

The study concludes with an overview of the results, including its accomplishments, limitations, and implications. In addition, future work areas are discussed, including potential improvements, new functionality, and opportunities for research.

Chapter 2 Literature Review

2.1 Understanding Indoor Air Quality

In addition to food and drink, the human body also needs oxygen to function properly. Breathing allows air to enter the lungs and circulate throughout the body. The filtered air is then inhaled into the lungs, where the oxygen is released into the blood and carried to the tissues via hemoglobin, where it can be used in cellular metabolism. Inhaled air is a complex gaseous mixture that consists primarily of nitrogen and oxygen but also contains tiny amounts of argon, carbon dioxide, water vapor, and other gases.

We breathe in about 10–20 m3 of air every day, or about 26,000 breaths. Pollutants in the air can have an adverse effect on human health since they are breathed into the body. Therefore, maintaining sufficient air quality is essential for protecting people's health.

People's health and well-being are profoundly affected by the indoor air quality where they spend most of their time. There is a wide spectrum of health issues caused by the emissions from construction materials, household appliances, human activities, and fuel use. Pollutants relate to both chemical substances and particles that are hazardous to human health. Air pollution results from the presence of pollutants in the atmosphere, the severity of which depends on both the amount of pollution produced and the speed with which it spreads. Natural causes, including plants, forest fires, emissions from soil and water, and radioactive decay, can potentially contribute to air pollution in addition to human activities (Figure 2.1). Air pollution lowers people's quality of life, and its detrimental effects on human health and the environment have sparked growing public concern in recent years.

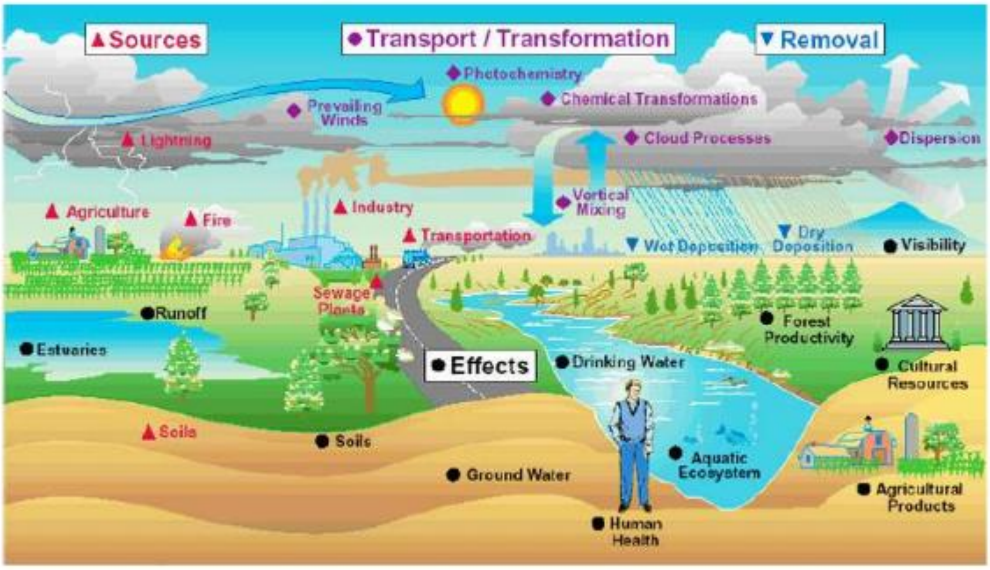
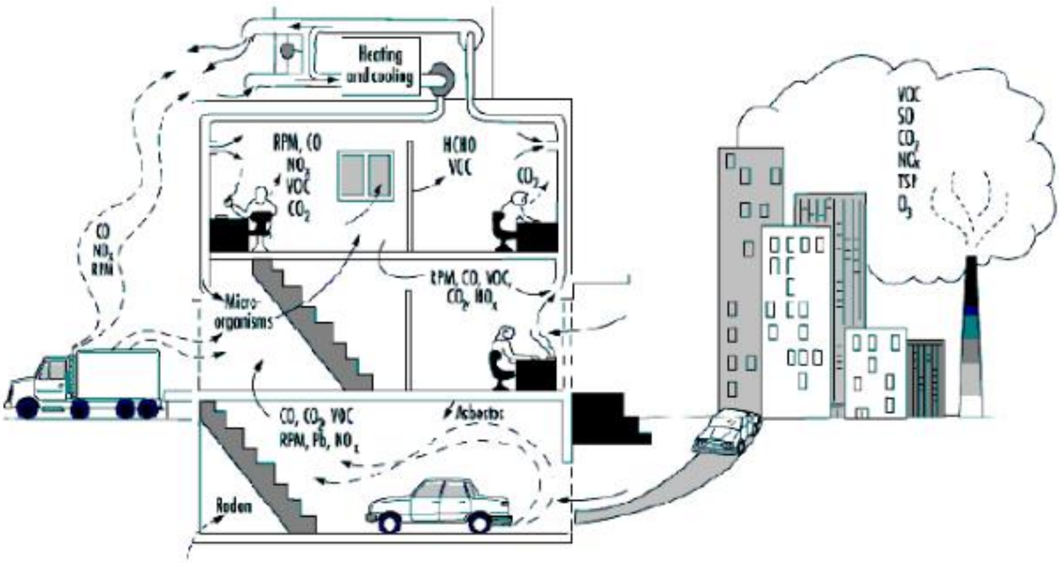


Figure 2.2.1: Pollution sources, transport, transformations, removal, and effects [3].

Indoor air quality refers to the quality of the air inside homes, workplaces, schools, and other indoor environments. There are many factors that influence and determine the quality of the indoor air, such as pollutants, most of which originate within the building, while others come from the external environment [4]. As shown in Figure 2.2 below, pollutants in the indoor environment may originate from both indoor and outdoor sources.



CO = carbon monoxide; CO_2 = carbon dioxide; HCHO = formaldehyde; NO_x = nitrogen oxides; Pb = lead; RPM = respirable particulate matter; VOC = volatile organic compounds.

Figure 2.2.2 The indoor and outdoor sources of pollution in the indoor environment of buildings [4].

Several organizations have attempted to describe air quality using a single index commonly known as the Air Quality Index (AQI), with the aim of providing easy access to information for the public. Despite this, there are no global standards, and each organization determines its own method of calculation. In most cases, pollutant risk is estimated over a specific period, and the result is then mathematically combined to produce the final index. The level of risk is usually indicated by a color-coded scale accompanied by this number. (Figure 2.3).

Figure 2.2.3 Common Air Quality Index (AQI).

2.2 Major Indoor Air Pollutants

Common indoor air pollutants include nitrogen oxides (NOx), sulfur dioxide (SO2), ozone (O3), carbon monoxide (CO), volatile and semi-volatile organic compounds (VOCs), particulate matter (PM), radon, and microbes. Some of these pollutants (such as NOx, SO2, O3, and PM) are present in both indoor and outdoor settings, whereas others may have their origins outside. Inorganic, organic, biological, and even radioactive substances can all contribute to air pollution. Air pollution can have different effects on different people based on factors such the pollutants toxicity, concentration, and duration of exposure. Sick building syndrome (SBS) is the most prevalent result, and it includes a wide range of symptoms from mild discomfort to severe illness, including nasal, eye, and throat irritation, skin problems, allergies, and more. Leaving the building where the sickness was experienced may be enough to alleviate the symptoms, even if the underlying reason remains unknown. Increasing the room's airflow has been shown to improve indoor air quality and decrease SBS [5]. Employee productivity is also impacted by the indoor air quality in the workplace. Wyon [6] observed that changes in interior environmental quality would have a strong and substantial effect on the performance of real office work, and that the performance of the work may be dramatically improved by removing typical indoor sources of air pollution.

2.2.1 Carbon Dioxide

Carbon dioxide (CO_2) is a colorless and odorless gas that serves as a significant indoor air pollutant. It acts as a simple asphyxiant and can also function as a respiratory stimulant. Human breath continuously emits carbon dioxide and water vapor, making it a prominent exhalation product [7]. The significance of carbon dioxide as a primary human emission has long been acknowledged, with Pettenkofer recommending a limit value of 0.1% CO_2 for adequately ventilated rooms, corresponding to approximately 700 parts per million (ppm) in bedrooms.

In the context of domestic energy use for cooking and heating, carbon dioxide emerges as the predominant combustion product. The main sources of CO_2 can vary, depending on the specific type of appliances used, including gas, kerosene, or wood-fueled systems. The introduction of combustion exhausts into the indoor atmosphere contributes to the overall presence of carbon dioxide [7].

CO_2 has been effectively employed as an indicator of human bio effluents for over a century [8]. Figure 2.4 illustrates the relationship between the concentration of CO_2 and the percentage of dissatisfied occupants in spaces where sedentary individuals constitute the primary pollution sources.

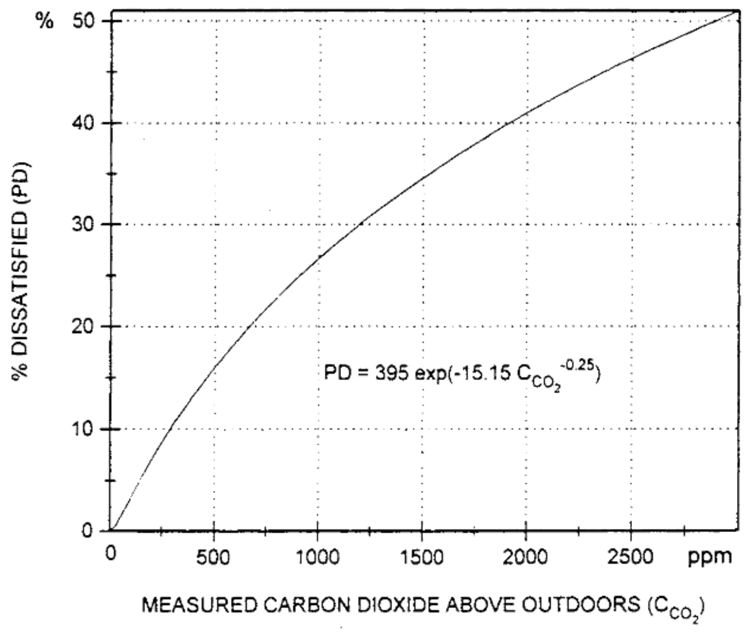


Figure 2.2.4 Carbon dioxide as an indicator of human bio effluents [6].

However, it is important to note that while CO2 serves as a valuable indicator of pollution originating from human activities, it may not adequately capture perceived air quality. Its limitations include the inability to account for pollution from non-CO2-emitting sources and undetectable hazardous air pollutants such as carbon monoxide, radon, benzene, and others [9].

2.2.2 Carbon Monoxide

Carbon monoxide (CO) is a colorless, odorless, and tasteless gas that arises from the incomplete combustion of carbon-based materials. It is considered one of the most prevalent and widely distributed air pollutants. The formation of carboxyhemoglobin (COHb) occurs when carbon monoxide binds with hemoglobin in the bloodstream, leading to the impairment of oxygen transportation and potential health hazards. In the indoor environment, carbon monoxide is primarily generated by unvented combustion appliances, particularly when operated in inadequately ventilated spaces. Furthermore, tobacco smoking represents a significant indoor source of carbon monoxide pollution.

2.2.3 Ozone

The ozone layer in the stratosphere plays a crucial role in absorbing ultraviolet radiation, thereby serving as a significant protector of the Earth. However, it is important to note that stratospheric ozone poses a burden on human health. Ozone, an invisible gas, exhibits potent oxidative properties and is characterized by a pungent odor. Its formation predominantly occurs during daylight hours, while its production diminishes during nighttime when photochemical reactions are absent. Due to its detection being closely associated with photochemical pollution, ozone serves as a key indicator of such pollution. External sources of ozone in the environment include ionizers and electrostatic air filters [10]. Meanwhile, indoor environments witness ozone emissions originating from laser printers, photocopiers, and electrical equipment.

As per the American Conference of Governmental Industrial Hygienists (ACGIH), ozone is categorized among the pollutants known to induce carcinogenesis. The subsequent presentation in Table 2.1 outlines the concentrations of O3 alongside their respective impacts on human health.

No.	O3 Concentrations (ppm)	Effects on Human Health
1	0.3	Irritation of the throat and nose
2	1-30	Fatigue and lack of coordination of movements
3	90	Pulmonary edema and fatality

Table 2.2.1 Concentrations of O3 and their Effects on Human Health.

2.2.4 Nitrogen Oxides

Nitric oxide (NO), nitrogen dioxide (NO2), and other gases collectively referred to as nitrogen oxides (NOx) are compounds that are present in the atmosphere. These gases have both natural and anthropogenic sources. Lightning and microbiological activity in soils contribute to the natural emission of nitrogen oxides, while human activities such as automobile emissions and energy production facilities are significant anthropogenic sources.

Among these gases, nitric oxide is primarily emitted by automobiles and represents a substantial portion of total NO emissions resulting from human activities. It is estimated that approximately 1/15 of total NO emissions in the atmosphere originate from anthropogenic sources [11]. In indoor environments, nitric oxide can be generated by heating devices, gas usage, and cigarette smoke. It is important to note that in the absence of combustion processes indoors, the concentration of nitrogen oxides is approximately halved compared to outdoor levels [4].

Nitrogen dioxide, a component of nitrogen oxides, plays a significant role in the formation of photochemical smog. It is worth mentioning that nitrogen dioxide is approximately four times more toxic than nitric oxide, although no reported cases of fatality are attributed to nitric oxide alone. However, exposure to nitrogen dioxide can lead to pulmonary edema. At concentrations of 100 ppm, it causes lung irritation, and at concentrations of 150-200 ppm, it can result in fatality [11]. Consequently, nitrogen oxides contribute to respiratory problems and have adverse effects on cardiovascular health.

2.2.5 Sulfur Dioxide

Sulfur dioxide (SO2) is a colorless gas with a pungent odor which can be detected at about 0.5 ppm. It mainly originates from the combustion of fossil fuels, which have high sulfur content, and its oxidation occurs through both photochemical and catalytic processes. It is readily soluble in water and can be oxidized within airborne water droplets. that is formed from the reaction of sulfur trioxide gas (SO3) with water. Together with other sulfur compounds and particulate matter is a major air pollutant all over the world due to its generation during combustion of fossil fuels [7].

Approximately 80% of anthropogenic sulfur dioxide emissions are attributed to the combustion of fossil fuels from stationary sources (industry and heating). Additionally, volcanic emissions and emissions from the chemical industry are sources of sulfur dioxide emissions, with the most significant contributors being petroleum refineries and copper processing plants [12]. In indoor environments, sulfur dioxide is generated by cigarette smoke and gases released during the operation of kerosene stoves [10].

2.2.6 Formaldehyde

Formaldehyde (HCHO) is a widely present and significant indoor air pollutant due to its frequent occurrence and strong irritation potential. It is the simplest and most common aldehyde found in the environment. While formaldehyde is a volatile compound, it is not easily detected by gas chromatographic methods commonly used for analyzing volatile organic compounds (VOCs). At normal room temperature, it exists as a colorless gas with a pungent odor. It is soluble in water and is commercially available in a solution of approximately 30% concentration or in polymerized form (paraformaldehyde) [7].

When exposed to temperatures above 150°C, formaldehyde decomposes into methanol and carbon monoxide, although uncatalyzed decomposition occurs slowly below 300°C. In the presence of sunlight, formaldehyde readily undergoes photooxidation, converting to carbon dioxide. It also reacts relatively quickly with other trace substances and pollutants present in the air, resulting in a short half-life in urban air under sunlight. Without the presence of nitrogen dioxide, formaldehyde has an approximate half-life of 50 minutes during the daytime. However, in the presence of nitrogen dioxide, the half-life reduces to around 35 minutes [13].

2.2.7 Radon

Radon (Rn) is a radioactive gas that is colorless, odorless, and tasteless. It is made from various materials such as bricks, wood, and concrete blocks, as well as from rocks such as lightweight stone and granite.

In indoor environments, radon (Rn) originates from heating processes (burning natural gas) and the evaporation of water. Therefore, in personal hygiene spaces, if proper ventilation is lacking, the issue of radon concentrations becomes significant [7].

2.2.8 Volatile Organic Compounds

Volatile Organic Compounds (VOCs) encompass a diverse range of organic compounds, including halogenated, oxygenated, and sulfur-containing compounds, which exist in a gaseous state within the atmosphere. These compounds are emitted from both liquid and solid sources, and their concentrations are typically higher indoors compared to the outdoor environment [7].

Furthermore, indoor environments also contain chloroalkanes, chlorofluorocarbons, benzene, methylene chloride, tetrachloroethylene, and formaldehyde. Sources of VOCs in the environment include trees and vegetation, with human activities contributing to approximately 15% of VOC emissions [14]. The specific sources of VOCs in indoor spaces are outlined in Table 2.2.

No	Source	Origin	Characteristics
1	Background emissions	• Building equipment • Building materials (insulation materials, treated wood, etc.)	Continuous and steady emission rate.
2	Intermittent emissions	• Human activities, office products • Human body (human odor) • Exterior building environment (ventilation systems) • Daily weather conditions	Halogenated, aliphatic, and aromatic compounds

Table 2.2.2 Main Sources of VOCs in the Indoor Environment of Buildings [14].

Exposure to elevated concentrations of volatile organic compounds can elicit several health effects, including nasal, throat, ocular, and dermal irritation. Additionally, individuals may experience symptoms such as nausea, headache, dizziness, and respiratory difficulties. Cognitive impairments, such as decreased concentration, weakened memory, and fatigue, have also been associated with VOC exposure. Prolonged exposure to VOCs can further contribute to dermatological disorders, renal and hepatic impairments, and even carcinogenesis [14].

2.3 Sources of Indoor Air Pollutants and Health Impacts

Table 2.3 provides an overview of the sources of various indoor air pollutants and their associated health impacts. According to the World Health Organization (WHO) [15], approximately 3 billion people worldwide still rely on traditional cooking and heating methods that utilize dirty solid fuels like waste wood, charcoal, coal, dung, and crop wastes. These practices lead to the emission of significant amounts of air pollutants such as sulfur dioxide (SO2), nitrogen oxides (NOx), carbon monoxide (CO), and particulate matter (PM). If indoor air is not adequately ventilated, these pollutants can accumulate, posing serious health risks to the inhabitants.

In addition to these outdoor-related pollutants, there are numerous anthropogenic sources of volatile organic compounds (VOCs) indoors. These sources include wooden construction materials, oil-based paints, fragrant decorations, and indoor plants. VOCs, such as formaldehyde, have the potential to be carcinogenic, while others like terpenes can react with ozone to form secondary fine suspended particles within the indoor environment [16]. Wallace highlighted the existence of numerous consumer products and building materials as indoor sources of toxic organics [17]. Radon is another significant indoor air pollutant and is the second leading cause of lung cancer in many countries, particularly in houses constructed with stone materials or poorly ventilated basements [18]. Biological sources, including pets, dust mites, and humans, also contribute to indoor air pollution.

The presence of these indoor air pollutants significantly increases the risk for individuals with respiratory conditions, such as asthma, as well as those with compromised or underdeveloped immune systems [19].

PM	Cooking stoves; fireplaces; smoking; outdoor air	Respiratory and cardiovascular illnesses
SO_2	Cooking stoves; fireplaces; outdoor air	Impairment of respiratory function
NO_2	Cooking stoves; fireplaces; outdoor air	Irritate the lungs and lower resistance to respiratory infection
CO	Cooking stoves; fireplaces; water heater; outdoor air	Highly toxic and fatal at a conc. 700 ppm
Ozone	Air cleaning device with high voltage; outdoor air	Asthma and allergic triggers
VOCs (such as formaldehyde, turpenes)	Building materials including carpet, plywood (emit formaldehyde); Paint and solvents; Clothing (after dry cleaning) (emits tetrachloroethylene, or other dry cleaning fluids); air fresheners, incense, other scented items; certain plants (emit turpenes)	Some are carcinogenic; can also trigger the formation of photochemical oxidants, such as peroxyacyl nitrates (PAN) and aldehydes, which cause eye irritation
Radon	Exuded from earth and rocks such as granite and gneiss in certain locations with low ventilated air and trapped inside houses	Radioactive; leading cause of lung cancer in non-smokers
Biological air pollutants (gasses and airborne particulates)	Pets (dander), human (dust from minute skin flakes and decomposed hair), dust mites (enzymes and μm-sized fecal droppings), inhabitants (methane), wall and air-duct (mold)	Increase risk for people with breathing problems, such as asthma sufferers, and with compromised or underdeveloped immune systems

Table 2.2.3 Source of various indoor air pollutants, and their health impacts [19].

2.4 Particulate Matter

Particulate matter (PM) refers to a complex mixture of solid and liquid particles suspended in the air. It is one of the most significant and widespread air pollutants, affecting both indoor and outdoor environments. Some particles, such as dust, dirt, soot, or smoke, are large or dark enough to be seen with the naked eye. Others are so small they can only be detected using an electron microscope. The size, composition, and sources of particulate matter vary, leading to diverse health and environmental impacts [20].

Particulate matter is categorized based on its aerodynamic diameter, which determines its behavior in the atmosphere and its potential to penetrate the human respiratory system. The size distribution of particulate matter ranges from coarse particles (PM10, diameter ≤ 10 micrometers) to fine particles (PM2.5, diameter ≤ 2.5 micrometers) and ultrafine particles (PM0.1, diameter ≤ 0.1 micrometers). EPA [20] is especially concerned about tiny particles that are 10 micrometers in diameter or smaller.

- **PM10**: inhalable particles, with diameters that are generally 10 micrometers and smaller; and
- **PM2.5**: fine inhalable particles, with diameters that are generally 2.5 micrometers and smaller.

To illustrate the scale of fine particles (Figure 2.4), consider an average human hair is about 70 micrometers in diameter – making it 30 times larger than the largest fine particle. These particles can be inhaled deeper into the lungs than larger particles, where they can cause serious health effects [20].

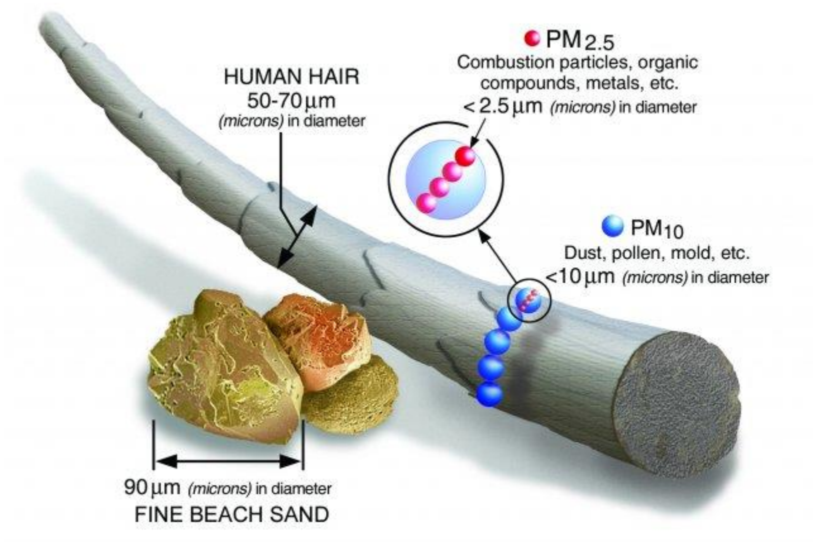


Figure 2.2.5 Size comparisons for PM particles [20].

2.4.1 Sources of Particulate Matter

Particulate matter comes in many sizes and shapes and can be made up of hundreds of different chemicals. They can originate from both natural and anthropogenic sources.

Natural sources include dust, pollen, sea salt, and volcanic eruptions. Anthropogenic sources involve various human activities such as combustion processes (e.g., industrial emissions, vehicle exhaust, and residential heating), industrial activities, construction and demolition, agriculture, and wildfires. These sources release particles of different sizes and chemical compositions into the air, contributing to the overall particulate matter levels. Particulate matter found indoors includes particles that come from outdoor air and particles that are generated indoors. Outdoor air brings particles indoors when it enters through windows and doors. PM can also enter through small openings and cracks in walls and foundations. [20]

Indoors, PM is generated by:

- Cooking
- Some cleaning activities
- Combustion activities
- Burning candles
- Use of fireplaces
- Use of unvented space heaters and kerosene heaters
- Tobacco and other smoking products
- Biological contaminants
- Animals
- Pests
- Plants
- Mold
- Printers
- Indoor chemical reactions

2.4.2 Health Effects of Particulate Matter

Health effects associated with PM2.5, PM10, and UFPs include respiratory problems, cardiovascular diseases, carcinogenesis, and milder symptoms such as coughing, phlegm production, and general discomfort According to the World Health Organization (WHO), the number of deaths will increase by 0.6% for every 10 g of PM10 per day and by 6% for every 10 g of PM10 per year. In order to determine whether particulate matter is toxic, it is necessary to consider a combination of factors, such as its size, its chemical composition, as well as whether it contains toxic ingredients. [21]

2.4.3 Measurement and Monitoring of Particulate Matter

Measurement of airborne particles is not an easy task since they are microscopic in nature. There have been several scientific methods proposed and used, which lead to different results based on particle size, particle type, and other environmental factors [22]. Most measurement devices are complex in their construction, requiring frequent cleaning and calibration, along with intricate measurement procedures. In addition, these difficulties result in measurement inconsistencies and high acquisition and operation costs [23]. In most cases, reference devices cost tens of thousands of euros, while cheaper commercial solutions usually exceed five hundred euros.

The optical method is one of the most economical methods for measuring the number of airborne particles. Based on scattering or absorption of light from the aerosol, conclusions are drawn regarding its quantity of airborne particles. In the case of scattering, the quantity of particles can be determined by a photodiode at an angle to the beam path, and their size can also be determined by using optical lenses and estimating the scattering pulse width [24]. There are many benefits of this method, such as low cost, ease of use, and real-time measurements. While the accuracy varies between 30% and 40%, it is the highest among other economical methods/devices [23]. It has been observed that the results deviate more from reality as the particle size increases.

Commercially, this technology is used in an increasing number of devices manufactured by traditional major manufacturers. Recently, manufacturers in Asia have introduced low-cost sensors using the same technology without certifications or calibration reports, but with impressive claims regarding measurement capabilities, size discrimination, and accuracy. By using low-cost airborne particle measurement sensors, organizations and individual users will be able to perform more thorough research in the field and monitor air quality at a mass scale. Consequently, the scientific community has demonstrated an immediate interest in comparing low-cost sensors to reference sensors and evaluating the potential of low-cost sensors.

2.5 Existing Methods for Indoor Air Quality Monitoring

Currently, indoor air pollution (IAP) poses a significant health risk, prompting researchers to investigate advanced sensor networks and communications technologies for monitoring indoor air quality (IAQ). The purpose of this summary is to provide an overview of existing IAQ monitoring systems, focusing on studies that address prominent IAP parameters.

The monitoring of indoor air quality has traditionally been carried out using conventional methods such as direct sampling and sensor-based approaches. Normally, direct sampling involves the collection of air samples manually and the subsequent analysis of these samples in a laboratory. Despite its accuracy, this method is time consuming, costly, and does not provide real-time data. On the other hand, sensor-based approaches use a variety of sensors to detect and measure IAQ parameters, including gas sensors, particulate matter sensors, and humidity sensors. Sensors such as these can be integrated into portable devices or fixed locations for continuous monitoring and data collection. However, sensor-based systems may differ in terms of accuracy and reliability, requiring calibration and maintenance on a regular basis [25].

In addition to remote sensing and satellite monitoring, internet of things (IoT) and smart building technologies, as well as machine learning and data analytics, there are advanced methods for monitoring IAQ. By utilizing satellite imagery, remote sensing techniques can monitor air quality on a large scale, allowing researchers to identify pollution sources, track trends in air quality, and assess mitigation measures. IoT and smart building technologies employ wireless sensor networks to collect IAQ data. Data from this system is analyzed by a central system to provide insights into the overall air quality situation. By integrating ventilation and HVAC systems, we are able to automate air quality control and optimize energy consumption. In order to enhance IAQ monitoring, machine learning and data analytics techniques can be used to identify patterns, correlations, and anomalies in the IAQ data, thus allowing for proactive identification of air quality issues and the development of personalized IAQ management programs [25].

A variety of emerging technologies offer innovative approaches to monitoring indoor air quality (IAQ), such as nanotechnology and artificial intelligence (AI). Nano sensors with high sensitivity and selectivity are capable of detecting air pollutants at low concentrations, while nanomaterials can be integrated into air filters, coatings, and building materials to eliminate contaminants and improve indoor air quality. The combination of artificial intelligence and sensor fusion provides a comprehensive assessment of indoor air quality, the identification of pollutant sources, and the prediction of IAQ-related health risks. In the future, these technologies will revolutionize the monitoring of indoor air quality [25].

In order to maintain a healthy and comfortable indoor environment, it is important to monitor indoor air quality. There are several conventional methods that can be used to assess IAQ parameters, including direct sampling and sensor-based approaches. The use of advanced methods, such as remote sensing, the Internet of Things, machine learning, and emerging technologies such as nanotechnology, offer new possibilities for comprehensive and real-time monitoring of indoor air quality. By integrating these methods and technologies, it is possible to develop more effective IAQ management strategies and to enhance the well-being and productivity of building occupants.

2.6 Role of IoT in Air Quality Monitoring: Previous Studies and Applications

Air quality monitoring is essential for understanding and mitigating the health impacts of indoor and outdoor air pollution. The Internet of Things (IoT) has enabled significant advances in environmental monitoring, including air quality monitoring. Throughout this section, we investigate the role of Internet of Things in air quality monitoring by examining its definition, principles, benefits, advantages, as well as the challenges and considerations associated with its implementation.

2.6.1 Definition and Principles of IoT

The concept of the Internet of Things (IoT) was introduced in 1999 by Kevin Ashton, a member of the Radio Frequency Identification (RFID) development community. In recent years, it has gained significance due to the proliferation of mobile devices, embedded communication, cloud computing, and data analytics. The IoT envisions a world where billions of interconnected objects, ranging from smartphones and home appliances to industrial systems and vehicles, can sense, communicate, and share information over IP networks. This interconnected network of objects generates vast amounts of data, which can be collected, analyzed, and used for planning, management, and decision-making purposes [26].

In general, the IoT is defined as a network of physical objects that extends beyond traditional computers and includes devices of different types and sizes. These objects, such as vehicles, smartphones, medical instruments, and even animals and trees, are connected and communicate with each other based on established protocols. There are three main types of interactions enabled by IoT: those between people, those between people and machines/things, and those between machines/things and machines themselves [26].

Essentially, the IoT envisions a world in which interconnected things and objects are ubiquitous, enabled by wireless and wired connections, and able to be uniquely addressed. As a result of these interconnected objects cooperating with each other, new applications and services emerge in areas such as energy, transportation, and urban planning. Furthermore, IoT allows objects to communicate information about themselves, making them recognizable and intelligent. In conjunction with the advancements in cloud computing capabilities and the transition to IPv6, which enables almost unlimited addressing capacities, this transformation aligns with the advancements in cloud computing capabilities [26].

An IoT platform consists of both software and hardware technologies, including RFID, wireless sensor networks, communication technology (such as Ethernet, Wi-Fi, Bluetooth, ZigBee, GSM, and GPRS), and microcontrollers. With these technologies, contextual information can be acquired, processed, and secured, which are the most important features that differentiate IoT from traditional internet systems [26].

IoT has several fundamental characteristics, including interconnection, the ability to provide services related to things, heterogeneity of devices and networks, dynamic changes in device states and numbers, an enormous number and scale of interconnected devices, safety concerns, connectivity, and compatibility across networks [26].

As shown in figure 2.6, the IoT architecture is composed of several layers of technologies. It consists of integrated objects equipped with sensors that gather real-time data. These sensors are connected to gateways and networks that provide a means of transporting the information generated by the sensors. To process and manage IoT data, the management service layer provides analytics, security controls, and process modeling. In the application layer, IoT applications are deployed in a variety of domains such as transportation, healthcare, agriculture, and energy to create "smart environments" [25].

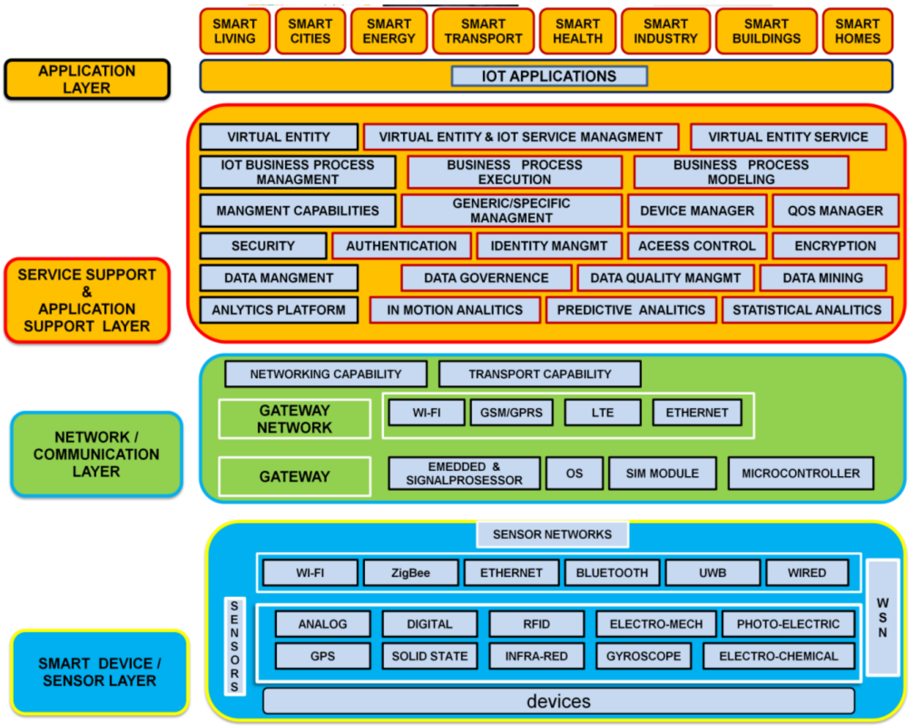


Figure 2.2.6 IoT Architecture [26].

The Internet of Things can assist in monitoring air quality by integrating sensors, data collection devices, communication networks, and cloud-based platforms.

Air quality monitoring by IoT involves the following principles:

- Sensor Integration: IoT systems for air quality monitoring integrate sensors to measure a variety of parameters, including particulates, gases, temperature, humidity, and more. Using these sensors, air quality conditions can be monitored in real time.
- Data Transmission: IoT devices transmit collected air quality data to a central monitoring system or cloud-based platform using wireless communication protocols such as Wi-Fi, Bluetooth, or cellular networks. As a result, remote access and real-time monitoring are possible.
- Data Analytics and Visualization: IoT platforms use data analytics and visualization techniques to process, analyze, and present air quality data. Using this method, users can easily interpret and understand air quality trends and patterns.

2.6.2 Benefits and Advantages of IoT in Air Quality Monitoring

The application of IoT in air quality monitoring offers several benefits and advantages. In terms of battery life and single hop communication capabilities, IoT monitoring systems are the most reliable solutions for measuring indoor air quality. These systems are also easier to maintain due to their lower latencies and power consumption. Additionally, IoT-based real-time monitoring systems are known as smart systems, which has attracted many researchers and manufacturers. According to experts, IoT systems can monitor a wide range of parameters without compromising performance. Studies carried out by Idrees et al. [27] and Sivasankari et al. [28] gave a new edge to the IAQ monitoring systems with impactful IoT architecture design.

2.6.3 Challenges and Considerations of IoT in Air Quality Monitoring

It is important to note that, while IoT offers numerous benefits, it also poses some challenges and considerations when it comes to monitoring air quality. A major concern is the security and privacy of personal information. It is critical to ensure the security of air quality sensors and IoT systems to prevent unauthorized access or data breaches. When sensitive or personal data is involved, the privacy of the data must be ensured. Furthermore, in order to ensure the accuracy and reliability of IoT sensors, calibration and maintenance are essential. During time, sensor drift and degradation may impact the accuracy and integrity of data on air quality. Additionally, IoT devices and platforms may employ different communication protocols and data formats, resulting in interoperability issues. The standardization of IoT components is crucial to ensuring compatibility and seamless integration. Finally, IoT devices typically use limited power sources, which are typically batteries. It is important to implement effective power management strategies as a means of maximizing device operational life as well as minimizing maintenance requirements. [25]

2.7 Existing IoT Solutions

An American company, Dylos, manufactures air quality sensors that are fully certified or scientifically advanced. It also offers a PM2.5 and PM10 measurement sensor, the DC17007, which are both priced at approximately €300 and €500, respectively. There is often a comparison in the literature between low-cost sensors and these sensors.

Nevertheless, Holstius et al. [29] report a low correlation between these measurements and reference measurements. Additionally, compared to low-cost sensors, they appear to have a poorer linear correlation with reference sensors, with R2 values ranging from 0.58 to 0.85 for PM2.5 and 0.15 to 0.18 for PM10 [30].

In 2012, the Air Quality Egg, an open-source and open-design device that brings awareness to the issue of low-cost indoor air pollution monitoring, conducted one of the most successful crowdsourcing campaigns of its time. Initially, this device was advertised as being able to measure NO2 and CO for just €100 and O3, VOCs, radiation, and particulate matter for approximately €250. Unfortunately, the complete device was never delivered, and the data monitoring platform shortly thereafter was discontinued. However, for the first time, air quality monitoring in indoor environments was of considerable interest, at least among the technologically advanced segment of the population.

Taking advantage of this interest, Air Visual launched a crowdsourcing campaign in 2016 to bring to market an indoor air quality measurement device that would measure PM2.5, PM10, and CO2. By sending the measurement results via the Internet and combining them with outdoor measurements, the company is able to estimate and predict the air quality.

A final mention should be made of Edimax's AirBox series of consumer devices, a Taiwanese company known for its quality consumer products. Through these devices, data can be transmitted to cloud computing and analyzed in a mobile application as well as monitored for PM, humidity, and temperature. This device uses the same low-cost sensor as the previous generation, and independent evaluations have demonstrated a correlation R2 of at least 0.85 for PM2.5.

2.8 Gap in the Literature

While considerable research has been conducted on the monitoring of indoor IAQ and the use of IoT for environmental monitoring, specific details of monitoring air quality with IoT devices are still lacking.

According to our literature review and the existing proposed solutions, there are no truly low-cost IoT systems that utilize low-cost sensors for monitoring indoor pollutants. Although existing IoT solutions have shown promise, they often come with a high price tag or require specialized technical expertise for installation and maintenance. By developing such a system, the quality of the indoor air can be monitored easily and in real time.

In addition, there has been little attention paid to integrating real-time data from air quality monitors based on the Internet of Things (IoT) with existing building management systems (BMS). Many buildings already have established BMS for controlling heating, ventilation, and air conditioning (HVAC). It would be beneficial to explore methods to seamlessly integrate IoT devices with these systems to better control indoor air quality parameters and implement automated actions based on the collected data.

Identifying high-risk conditions and notifying individuals sooner if they are present in the environment would be possible if these gaps were addressed. Furthermore, it can be used in conjunction with other sensors and external environmental data to identify pollution levels as well as suggest methods for reducing them. It is possible to reduce the amount of pollutant infiltration into the indoor environment by closing the windows, and to reduce the concentration of particles by opening the windows and ventilating. In the future, the additional knowledge may assist users in actively reducing pollution levels through energy-saving actions or a change in behavior, which could reduce pollution levels.

Chapter 3 Methodology

3.1 System Architecture

The purpose of this chapter is to provide an overview of the structure of the proposed system. A short description of the components of the system is provided, along with their roles and how they communicate with one another.

3.1.1 IoT Device Hardware Configuration

The IoT device is a crucial component of the system implemented. The device is composed of a wireless processing unit and various peripheral sensors. The specific processing unit used can be configured either to operate as a Wi-Fi access point or to connect to a preexisting Wi-Fi network. As a result of this flexibility, data can be retrieved and handled from Wi-Fi-connected devices, such as Android mobile devices, or devices on a WAN/LAN network. It is equipped with a Real Time Clock (RTC) for accurate timestamping, as well as several sensors, including:

- Temperature Sensor: Measures the ambient temperature.
- Humidity Sensor: Measures the relative humidity of the environment.
- PM Sensor: Detects and measures the concentration of particulate matter in the air.
- TVOC Sensor: Monitors the TVOC present in the surroundings.
- eCO2 Sensor: Measures the level of equivalent carbon dioxide (eCO2) in the air.

3.1.2 Web Interface For Configuration and Data Visualization

The second part of the implemented system involves a web interface hosted on the IoT device's webserver. The web interface serves several purposes, allowing users to configure the IoT device according to their specifications. Using the web interface, users can alter Wi-Fi settings, select sensor preferences, and adjust data collection intervals. Furthermore, the web interface provides a user-friendly interface for visualizing the sensor data. Using this application, users are able to view live sensor readings, historical data, and interactive charts in real time. By visualizing the information, it is easier to understand it and identify trends and patterns.

3.1.3 Communication Protocol

In order to facilitate communication between the IoT device and the web interface, the WebSocket protocol is used. Using WebSocket, you can communicate with your device and web interface in real time, bidirectionally. This protocol ensures that sensor readings and device status updates are promptly reflected in the web interface thanks to efficient and instant data transmission. By utilizing WebSockets, you can present a responsive and interactive user experience to users.

3.1.4 Remote Data Storage and Accessibility

The third part of the implemented system involves the storage and access to data over the Internet. Through the use of the cloud, the sensor data collected is stored securely, ensuring its integrity and reliability. Due to its cloud-based storage capabilities, it offers convenience and flexibility when accessing data from any internet-connected device. In addition, the user will be able to view historical data, compare readings over time, and generate reports for further analysis. Furthermore, remote data storage can accommodate large volumes of data without affecting IoT device performance.

The following chapters provide a detailed description of how these components are implemented.

3.2 Hardware Development

3.2.1 IoT Prototyping

In recent years, technological advancements have dramatically reduced the cost of embedded systems, network infrastructure, sensors of all types, and devices that are used for the programming and control of systems.

It is common today for cell phones to include processors that are more powerful than those found in desktop computers of a few years ago. At the same time, it incorporates a variety of sensors and electronic components that were previously only available in specialized laboratories, such as three-axis accelerometers, magnetometers, thermometers, and others. All of these devices have the ability to communicate with the internet via wireless networks, and with other less intelligent devices that can provide information through low-power technologies (such as Bluetooth/BLE). Our everyday lives have already been impacted by devices such as cardiac monitoring systems, access control systems, smart watches, smart scales, and similar devices.

In spite of the reduced cost and increased availability, connecting and controlling sensors still requires specialized electronic design and programming skills, so the benefits are limited to individuals with deep expertise or those using ready-made commercial solutions that are limited in their expansion capabilities and have minimal or no adaptability to meet the specific needs of their users.

Arduino

An open-source platform for embedded electronic systems, Arduino, was developed in 2005 and emerged as a groundbreaking method for integrating microcontrollers with sensors.

The majority of these development boards are based on the ATMega series of microcontrollers, which are user-friendly and cater to both beginners and enthusiasts. One notable feature of these boards is the expansion headers, which are known as shields in Arduino lingo. Shields enable the attachment of additional modules with enhanced capabilities and features. The input/output pins of the original device are seamlessly connected to the top side of the expansion board as a result of the innovative design of the board. This allows multiple expansion boards to be stacked simultaneously.

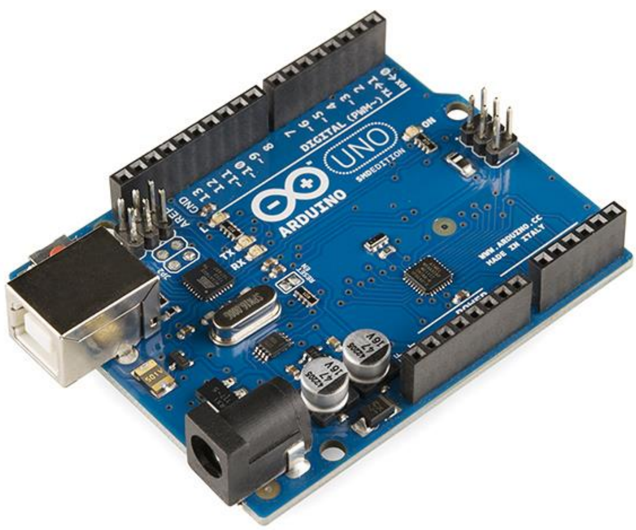


Figure 3.1 Arduino Uno.

Among the most popular and widely used boards is the Arduino UNO (Figure 3.1). It is equipped with an ATMEL ATMega328P microcontroller that delivers exceptional performance. Due to the lack of USB connectivity on the microcontroller, data transfer requires the use of a USB to RS232 converter.

The success of Arduino can be attributed to the bootloader, a compact program that runs during the initialization of the device, eliminating the need for external programming hardware.

Considering the limited processing power of 8-bit microcontrollers, Arduino incorporates hybrid boards. By combining a microcontroller with a 32-bit ARM processor, the Arduino DUE is able to provide unprecedented functionality. In recent years, newer Arduino devices have been replacing microcontrollers with more advanced options.

3.2.2 Processing Unit

The primary component of a sensor system is the processor. The selection of a processor unit must take into account several factors, including the cost, the power consumption, the performance, the ease of integrating sensors, and the peripheral communication interface.

FireBeetle ESP32

For our project, we have selected the FireBeetle ESP32 development board (Figure 3.2) from DFRobot. The FireBeetle series from DFRobot is specifically designed for low-power consumption and IoT applications. It incorporates a Dual-Core ESP-WROOM-32 module, enabling wireless & Bluetooth dual-mode communication as well as MCU functionality.

Figure 3.2 FireBeetle ESP32.

Specification

- Operating voltage: 3.3V
- Input voltage: 3.3V~5.5V
- Support electric current of low power consumption: 10 µA
- Support maximum discharge current: 600mA@3.3V LDO
- Support maximum charge current: 500mA
- Support USB charging.
- Processer: Tensilica LX6 dual core processor
- Frequency: 240MHz
- SRAM ： 520KB
- Flash ： 16Mbit
- Wi-Fi standard ： FCC/CE/TELEC/KCC
- Wi-Fi protocol: 802.11 b/g/n/d/e/I/k/r (802.11n, high speed can reach to 150 Mbps), converge A-MPDU and A-MSDU, supporting 0.4us protecting interval.
- Frequency range: 2.4~2.5 GHz
- Bluetooth protocol: Comply with BR/EDR/BLE standard of Bluetooth v4.2.
- Bluetooth audio: the current under low power consumption of CVSD and SBC is 10µA
- Operating current: 80mA in average
- Frequency range: 2.4~2.5GHz
- Support one-key downloading.
- Support micropython.
- On-chip clock: 40MHz crystal and 32.768 KHz crystal.
- Digital I/O: 10 (default setting of arduino)
- Analog input: 5(default setting of arduino)
- SPI: 1 (default setting of arduino)
- I2C: 1 (default setting of arduino)
- I2S: 1 (default setting of arduino)
- LED_BUILTIN ： D9
- Interface: FireBeetle series compatible
- Operating temperature: -40℃~+85℃
- Dimension: 29 × 58(mm)/1.142 x 2.283(inches)
- The dimension of mounting hole: inner diameter 3.1mm; outer diameter 6mm

Board Overview

ESP32 development board (Figure 3.3) features 30 GPIO (General-Purpose Input/Output) pins offering flexibility for various types of connectivity. As a result of the pin multiplexing capability of the chip, these pins can be configured to serve as ADC inputs, DAC outputs, or even touchpads.

As an important note, the ESP32 chip requires a 3.3V power supply and operates at 3.3V logic levels. However, the GPIO pins are not tolerant of exposure to 5V. Therefore, when connecting them to external components that operate at logic levels greater than 5V, it is necessary to incorporate intermediate circuitry capable of shifting the logic levels to the appropriate levels. Figure 3.3 illustrates all the versatile functions that can be achieved with each pin through proper chip programming.

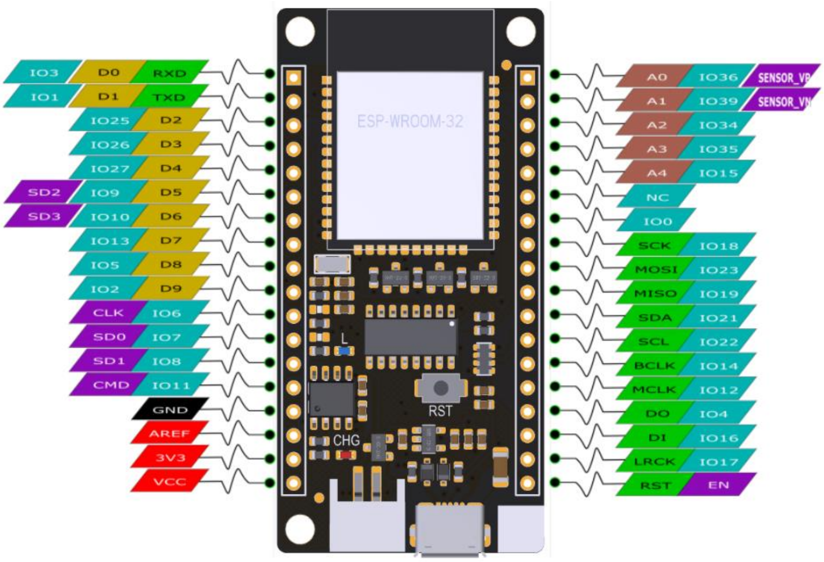


Figure 3.3 FireBeetle ESP32 Pinout.

Considering its power characteristics, the development board can be powered either through the Micro USB connector on the board or by using the Vin pin. Once powered, it generates a stable 3.3V voltage at the 3V3 pin and supplies up to 600mA of current to external peripheral devices. It is noteworthy that when it is in deep sleep, it consumes only 10 mA of electrical current.

3.2.3 Sensors

Following the selection of the processor unit, the next step is to choose the sensors. The following selections have been carefully selected based on the type of application, the environment in which they will be used, as well as accuracy and precision.

PMS5003

The Plantower sensor was identified by all researchers in our literature review as being one of the most reliable and linearly consistent low-cost particulate matter sensors. The PMS5003 sensor was therefore selected (Figure 3.4).

Figure 3.4 PMS5003.

A PMS5003 sensor is an affordable option (approximately 20-30 euros) with a measurement range of 0-500 µg/m3 (theoretical maximum of 1000 µg/m3), a resolution of 1 µg/m3, and manufacturer reports an accuracy of 98% for particles less than 5 µm, an error of 10% in the range of 100-500, and a disturbance of 10 units in the range of 0-100.

It is necessary to wait 30 seconds after activation and before retrieving data because the fan's performance is reduced at first. As stated by the manufacturer, the sensor is not recommended for use in environments with particle concentrations of more than 300g/m3 for more than 50% of the year and more than 500g/m3 for more than 20% of the year, in high humidity environments, or in outdoor spaces without protection from weather factors.

Data transmission is digital, using a serial protocol at 9600 baud (8N1) with a voltage level of 3.3 V. Measurement packets consist of 32 bytes, including control characters, data sets, and integrity checks. The sensor is capable of automatically sending measurement data when it is available or upon request through a control command. Additionally, it is equipped with a sleep mode that conserves energy.

Specification

- Range of measurement: 0.3~1.0；1.0~2.5；2.5~10 μ m
- Effective Range: 0~500 μ g/m³
- Maximum Range: * ≥1000 μ g/m³
- Resolution: 1 μ g/m³
- Standard Volume: 0.1L
- DC Power Supply: Typ:5.0 / Min:4.5 / Max: 5.5V
- Active Current: ≤100 mA
- Standby Current: ≤200 μ A
- Working Temperature Range: -10~+60 ℃
- Working Humidity Range: 0~99%
- Storage Temperature Range: -40~+80 ℃
- Sensor Module Dimensions: 50 × 38 × 21mm

Pin Identification and Configuration

No	Pin Name	Description
1	VCC	Power supply 3.5V to 5.5V
2	GND	Connected to the ground of the circuit
3	SET	Set pin
4	RX	Serial port receiving pin
5	TX	Serial port sending pin
6	RESET	Module reset sign
7	NC	No Connection and hence not used
8	NC	No Connection and hence not used

Table 3.1 PMS5003 Pin Identification and Configuration.

DHT22

This DHT22 sensor, manufactured by Aosong Electronics, has earned an outstanding reputation for its measurement accuracy and ease of use. It was used to investigate potential correlations between various environmental factors and recorded values. In addition, it served as a reference sensor for calibrating other sensors.

Figure 3.5 DHT22.

The sensor uses a conductive polymer element to measure capacitance. For temperature readings, it is factory calibrated to ensure a maximum deviation of less than half a degree Celsius, and for air relative humidity readings, it is calibrated to ensure a maximum deviation of less than two percent. Temperature measurements range from -40°C to 80°C, while relative humidity measurements range from 0% to 100%.
The DHT22 sensor is notable for its relatively long measurement cycle time, as it requires a minimum of 2 seconds for each measurement.

Despite having four pins, only three of them are utilized. The first two pins are dedicated to power supply and ground connections, while the third pin facilitates data transmission.
In order to communicate with a microcontroller, the sensor employs a proprietary protocol that uses timing signals to estimate the bit levels. This protocol differs from the widely known 1-wire protocol developed by Dallas.

Specification

- Operating Voltage: 3.5V to 5.5V
- Operating current: 0.3mA (measuring) 60uA (standby)
- Output: Serial data
- Temperature Range: -40°C to 80°C
- Humidity Range: 0% to 100%
- Resolution: Temperature and Humidity both are 16-bit
- Accuracy: ±0.5°C and ±1%

Pin Identification and Configuration

No	Pin Name	Description
1	VCC	Power supply 3.5V to 5.5V
2	DATA	Outputs both Temperature and Humidity through serial Data
3	NC	No Connection and hence not used
4	GND	Connected to the ground of the circuit

Table 3.2 DHT22 Pin Identification and Configuration.

ENS160

Fermion's ENS160 Air Quality Sensor (Figure 3.6), featuring ScioSense's cutting-edge ENS160 sensor chip, is specifically designed for monitoring indoor air quality. The sensor is capable of detecting multiple IAQ parameters such as Total Volatile Organic Compounds (TVOC), equivalent Carbon Dioxide (eCO2), and Air Quality Index (AQI).

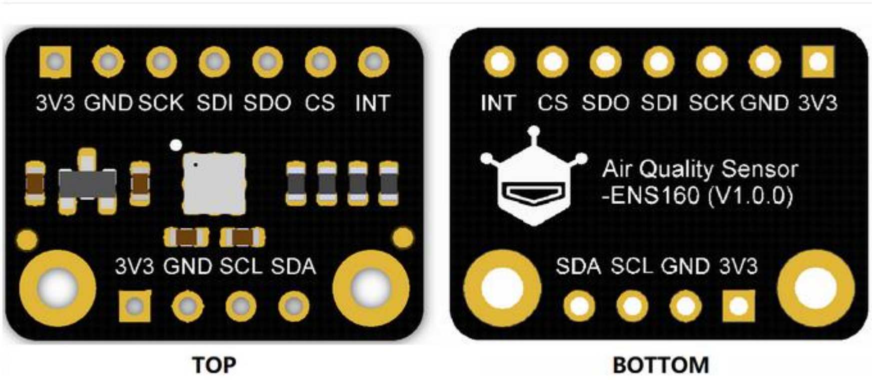


Figure 3.6 ENS160 Air Quality Sensor

The innovative TrueVOC™ technology, based on metal oxide (MOX) technology, sets the ENS160 sensor apart by delivering exceptional accuracy, rapid response time, and robust anti-interference capabilities. As a result of the sensor's intelligent on-chip algorithms, it is able to provide quick and comprehensive information regarding the environment in an understandable manner.

It is recommended that the sensor be preheated for three minutes prior to use in order to facilitate faster and more accurate data acquisition. This ensures that accurate data is obtained quickly for timely analysis and action. In addition, the sensor is equipped with a built-in automatic baseline correction algorithm, ensuring long-term stability. Through the use of this feature, the sensor can be assured that it will remain reliable and accurate for an extended period of time.

Fermion's ENS160 Air Quality Sensor provides accurate and real-time information to support a wide range of indoor air quality monitoring applications. It is well suited for applications such as air purification/home automation devices, environmental pollution detection, HVAC/ventilation systems, building automation/smart thermostats, and electrical appliances/range hoods.

Specification

- Power Supply Voltage: 3.3V
- Working Current: 29mA
- Warm-up Time: <3 minutes
- Interface Mode: I2C, SPI
- I2C Address: 0x52, 0x53(Default)
- Operating Temperature Range: -40℃~85℃
- Working Humidity Range: 5%RH~95%RH
- eCO2 Measurement Range: 400ppm~65000ppm
- TVOC Measuring Range: 0ppb~65000ppb

Pin Identification and Configuration

No	Pin Name	Description
1	3V3	Power supply 3.3V
2	GND	Ground
3	SCL	I2C clock line
4	SDA	Connected to the ground of the circuit
5	SCK	Serial clock
6	SDI	Serial data input
7	SDO	Serial data output
8	CS	Chip-select
9	INT	Interrupt Pin

Table 3.3 ENS160 Pin Identification and Configuration.

3.2.4 Other Peripheral Devices

RTC DS1307

DS1307 is a low-cost, highly accurate real-time clock module. The system measures time from years down to seconds, including leap years up to the year 2100. It is powered by a voltage ranging from 3.3V to 5V and communicates via the I2C protocol. If the main power supply is disconnected, the device can maintain timekeeping by using a LIR2032 or CR2032 3.3V battery. As long as the clock is programmed once, it will continue to function even after the battery has been removed.

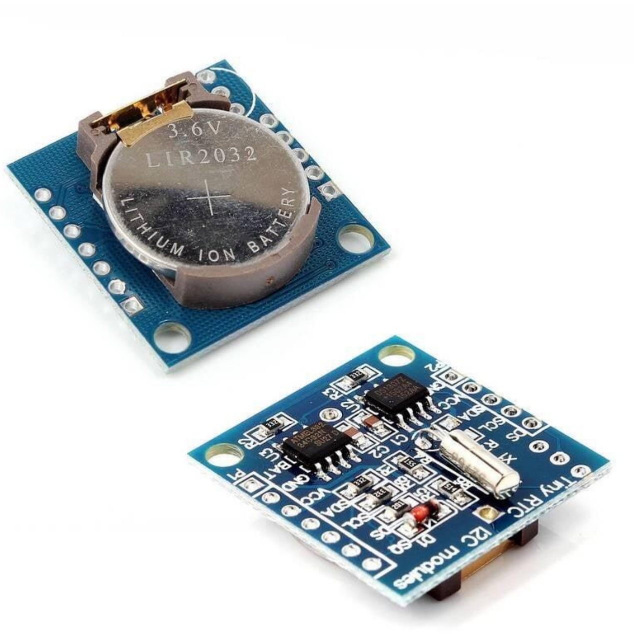


Figure 3.7 DS1307 RTC Module.

3.2.5 Prototype Development

The prototype was carefully developed on both hardware and software levels (Software development will be addressed in a subsequent chapter), employing a systematic, iterative, and evolutionary methodology. At each stage, incremental changes were introduced, allowing for immediate evaluation of their impact. Thus, adjustments could be preserved, refined, or discarded in subsequent iterations. As a result of this dynamic process, assumptions were able to be confirmed or corrected much more quickly as opposed to a prolonged period of theoretical design and direct implementation.

Development of Initial Prototype

In the initial phase of the project, all sensors were connected to the FireBeetle ESP32 development board using a breadboard. The purpose of this step was to verify the functionality of the sensors and determine the appropriate wiring arrangement for the sensors. It quickly became apparent that there was only one serial port on the ESP32 board, which was already allocated to the USB serial monitor or the RX/TX pins. Serial connections were also required for both environmental sensors. Fortunately, the Arduino framework provided a solution to this limitation. Utilizing the capabilities of the library, additional "software" serial ports were created, allowing for simultaneous use of the USB serial monitor and the environmental sensors. After iterative testing and adjustments, all the sensors were successfully connected, enabling accurate data retrieval. It was thoroughly tested to ensure that the device worked properly, and data could be transferred. Proof of concept was achieved, serving as a foundation for evaluating future development processes and determining next steps.

As the feasibility of the initial prototype was confirmed, the focus shifted to evaluating network connectivity. Another challenge was encountered as the ESP32's power consumption peaked during network scanning. This exceeded the board's 0.6 mA limit when combined with the sensors and other modules. The issue was addressed with the introduction of an external power supply. By using a DCJ0202 Female Jack, power was provided to the board. In order to mitigate voltage spikes and fluctuations, two electrolytic capacitors were used: 470uF and 100uF. For efficient voltage regulation, a voltage regulator chip such as the LM7805 was chosen, which can handle input voltages of 7V to 35V. However, it is recommended to stay within the 15V range to optimize performance and minimize heat dissipation. ESP32's Vin pin was connected to the voltage regulator's output, while GND was connected to ground. Using a 12V DC 1A adapter, reliable power was provided. In addition to a switch that turns the device on and off, an LED indicator confirms the device's power status visually.

In order to improve system functionality, a fan was integrated into the setup. As a result of the addition of the fan, the airflow around the sensors was optimized, improving performance and accuracy as soon as the device was activated.

Schematic Diagram

A schematic was essential for keeping track of all the connections in the project. For this purpose, EasyEDA, an online schematic editor, proved to be an ideal tool. It provided an easy method of creating and documenting the components and their connections. This schematic diagram (Figure 3.8) illustrates how everything discussed earlier fits together visually.

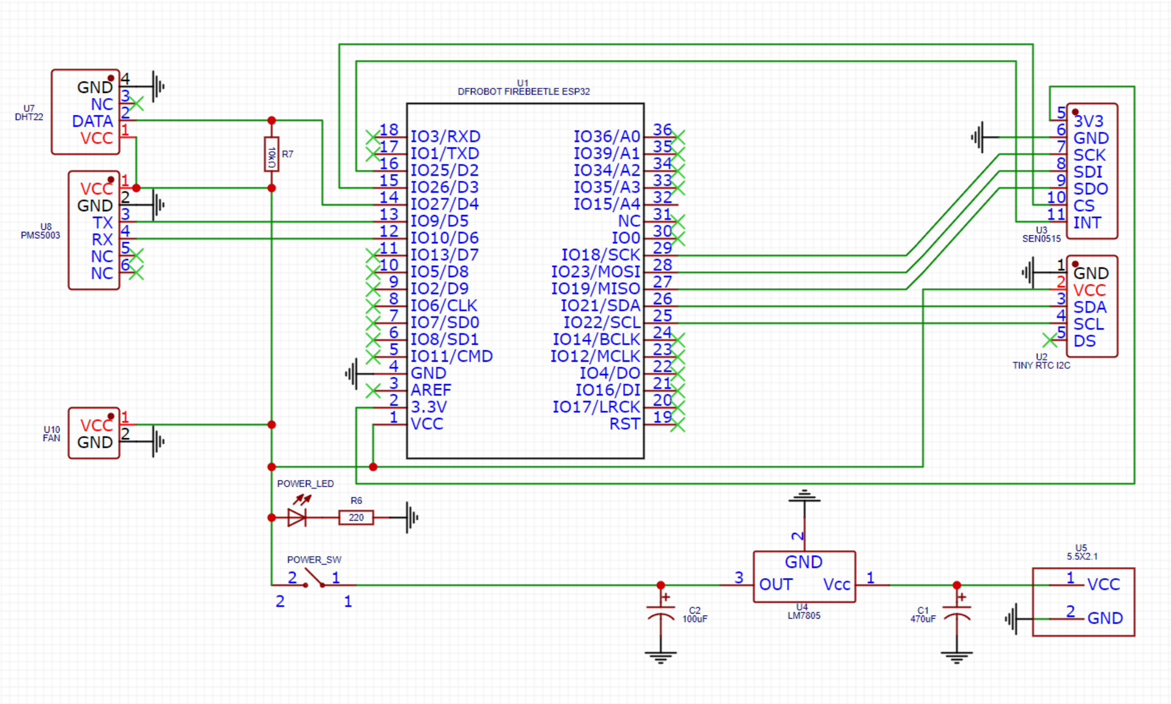


Figure 3.8 Initial Prototype Schematic Diagram.

When troubleshooting, the schematic proved invaluable. Whenever there was a problem or something did not work as expected, the wiring diagram served as a guide to identify wiring errors or other potential problems. It also serves as a reference for future modifications or upgrades.

The schematic represents a bird's-eye view of the project. Essentially, it serves as a roadmap, illustrating the interrelationships between the various components. A well-defined schematic simplifies the process of understanding and modifying the project.

Using EasyEDA simplified the process even further. With the intuitive interface, placing and connecting components was easy, enabling a smooth schematic design process.

Improvements and Final Prototype

Initially, the direct display of sensor readings was not considered in the design. It was assumed that the web interface would meet the requirements. Nevertheless, it became apparent that retrospective monitoring outside a controlled environment made it difficult to correlate the measurements with pollution activities. Therefore, a real-time presentation of the current situation was required in order to identify and evaluate potential countermeasures.

To accomplish this, Nextion's LCD display (Figure 3.9) was integrated into the system. Nextion displays are equipped with an ARM processor that controls the display graphics, including buttons, text, images, and variables independently. Nextion's editor (Figure 3.10) provided a dedicated platform for creating and controlling visual elements.

Figure 3.9 Nextion LCD.

Nextion Editor

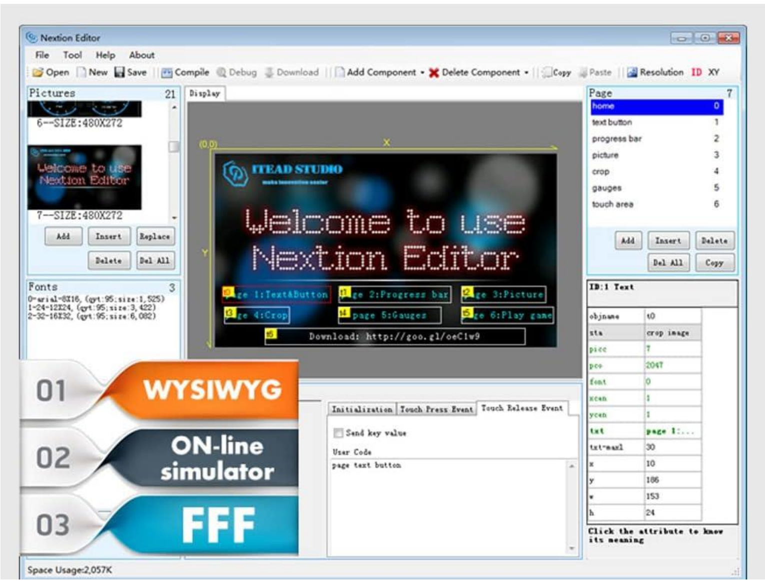


Figure 3.10 Nextion Editor.

Communication between the display and the ESP32 microcontroller is accomplished using a serial communication protocol, which is quite simple, requiring only two wires. With the implementation of another software serial port, the EPS32 is able to send sensor values and receive data from the LCD as required.

For the purpose of uploading the display program, an external microSD card is used. Nextion editor output files are saved on a microSD card, which is inserted into the display's card reader while the display is off. Once the device is powered on, the program is automatically uploaded to the display. As soon as the upload is complete, the microSD card can be removed, the power can be switched back on, and the air quality monitor will begin to display the new information.

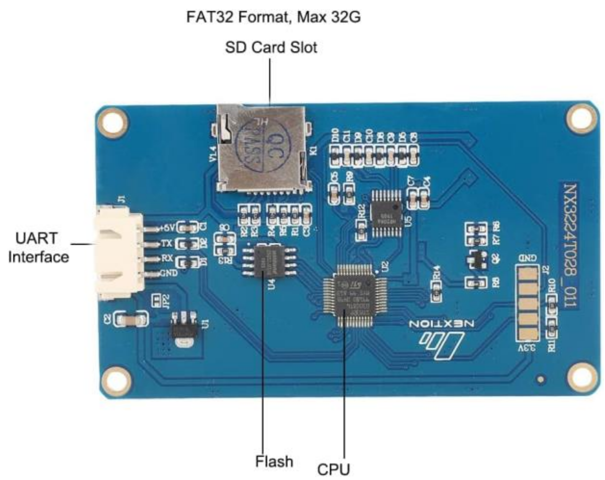


Figure 3.11 Nextion LCD Board Overview.

While utilizing the prototype, portability emerged as a significant concern, since data had to be collected from a number of locations. For this reason, the device was equipped with an 18650 Battery Shield (Figure 3.12). The purpose of this shield is to charge the 18650 battery and power the ESP32. It can be powered either via the USB output (type A) or through the six available outputs (soldering pins) on each side of the board, providing 5V or 3V power options. The shield features a charging circuit that includes an LED indicator to show battery charge progress.

Figure 3.12 Battery Shield v3.

In order to ensure a smooth transition between the external power source and the battery, a relay has been incorporated into the system. The IN pin of the relay is connected to the OUT pin of the regulator, while the normally open (NO) pin is also connected to the battery shield output. A schottky diode is placed between the relay and the battery shield, allowing current to flow from the battery to the relay but not in the opposite direction. The common pin of the relay is connected to the device's VCC, enabling it to draw power from the battery when there is no external power source present, as well as from the external power source when it is present. Additionally, a switch allows the user to control the charging from an external power source.

During the test phase, it became evident that the LM7805 regulator was generating excessive heat, causing an undesirable impact on the sensors' functionality and accuracy. In light of this observation, a decision was made to remove the LM7805 regulator from the setup. Instead, a conventional external power supply was introduced to provide the necessary 5V and 1A power requirements.

Additionally, during the testing phase, it was observed that the 18650 Battery Shield exhibited reliability issues. To address this concern and ensure a more robust power supply, a decision was made to replace the problematic component with a modified JX887Y (Figure 3.13). The JX887Y module, originally designed as a replacement part for power banks, proved to be a suitable alternative. The replacement process involved integrating the modified JX887Y module with an 18650-battery holder. This combination offered a more reliable and stable power source for the system.

Figure 3.13 JX887Y.

Furthermore, a couple of debug LEDs were incorporated into the system for the purpose of providing visual indications of the sensor and Wi-Fi status. Following these modifications, the final schematic diagram is shown in figure 3.14.

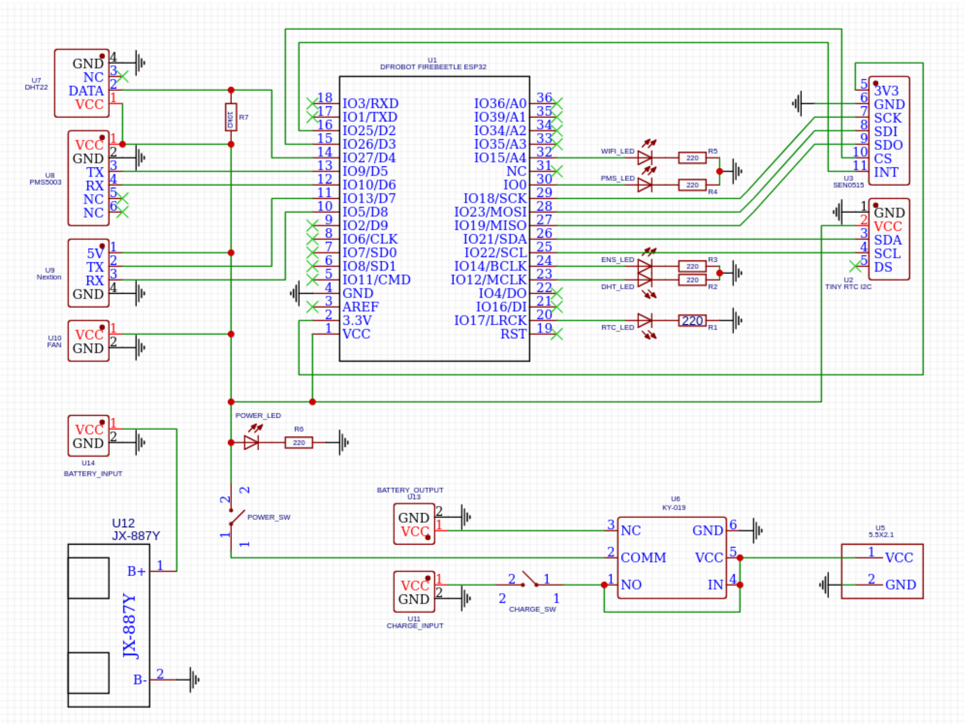


Figure 3.14 Final Schematic Diagram.

3.2.6 PCB Design

The process of creating the PCB for this project was made easy thanks to tools like EasyEDA. Using EasyEDA's user-friendly interface, you can quickly and easily create electronic circuits by selecting electronic components from a library (Figure 3.14). It allows access to a wide range of components from different manufacturers and even provides a collection of user-contributed components, making it convenient to find the necessary parts for the project.

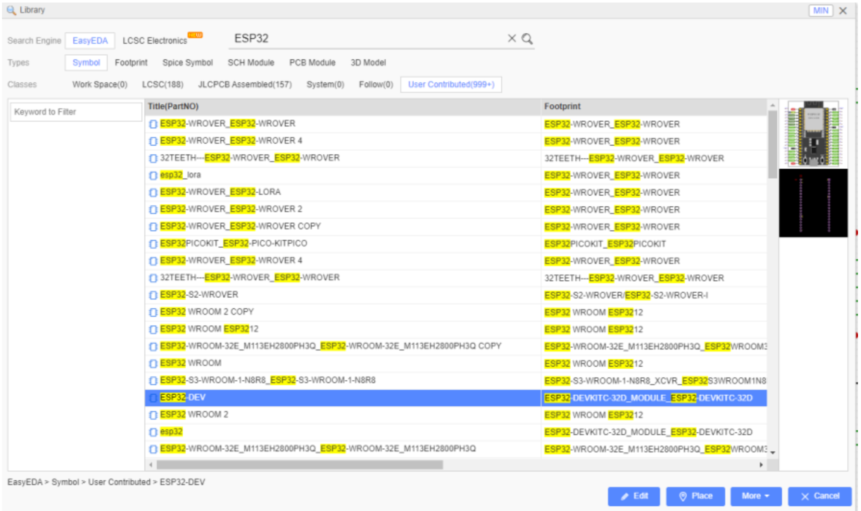


Figure 3.15 EasyEDA Library.

The PCB layout was generated based on the finalized schematic. The components were arranged according to preferences, and the Auto Route feature in EasyEDA automatically created the required connections between them (Figure 3.15). Manual adjustments could be made if needed. Specific design rules could be set to control trace routing, such as defining trace widths and other parameters.

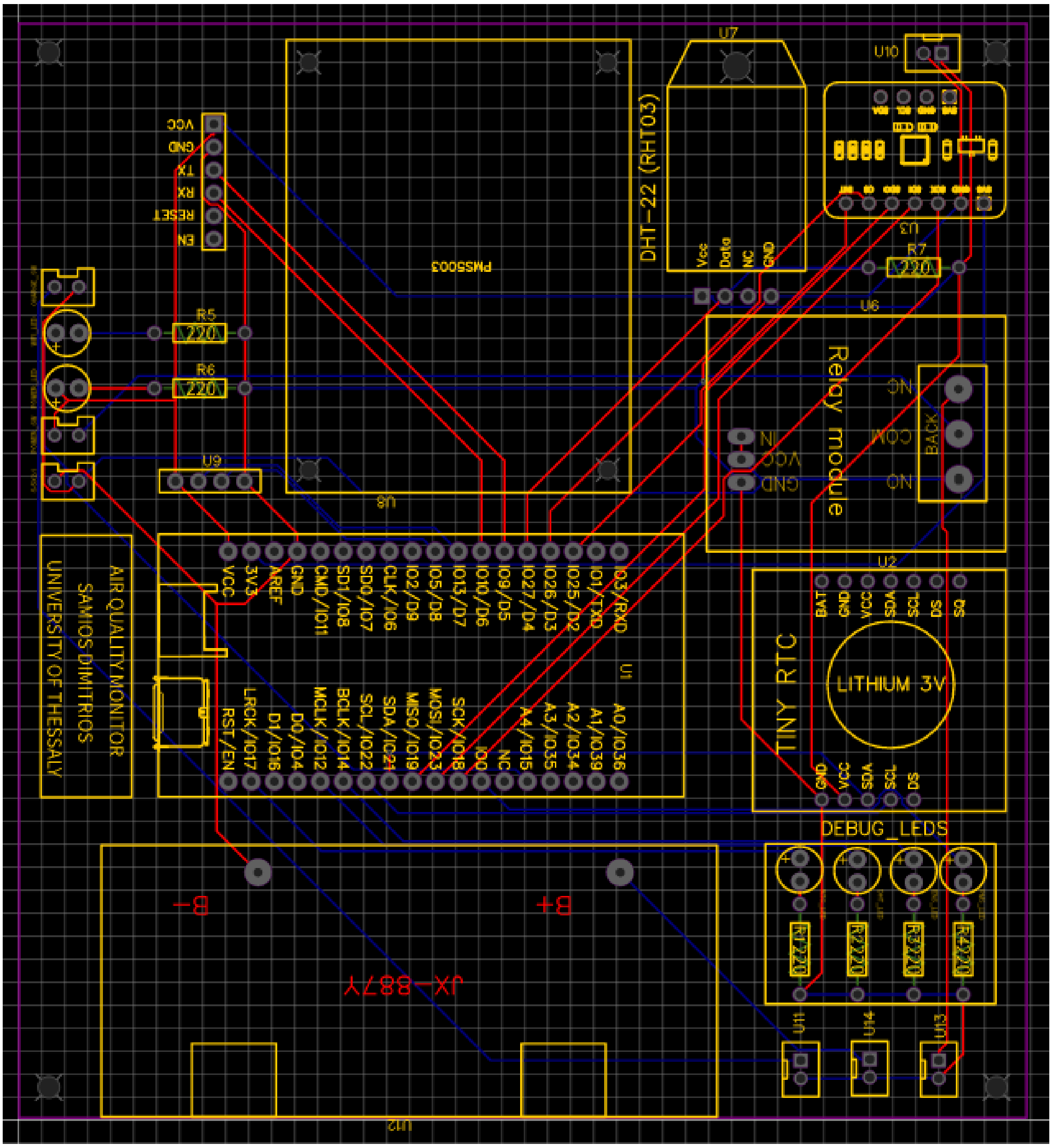


Figure 3.16 EasyEDA AutoRoute.

Once the PCB layout was completed (Figure 3.16), the necessary files, including Gerber and NC Drill files, were generated. These files contain essential information for PCB fabrication. They were compiled into a single zip file, which was then ready for manufacturing.

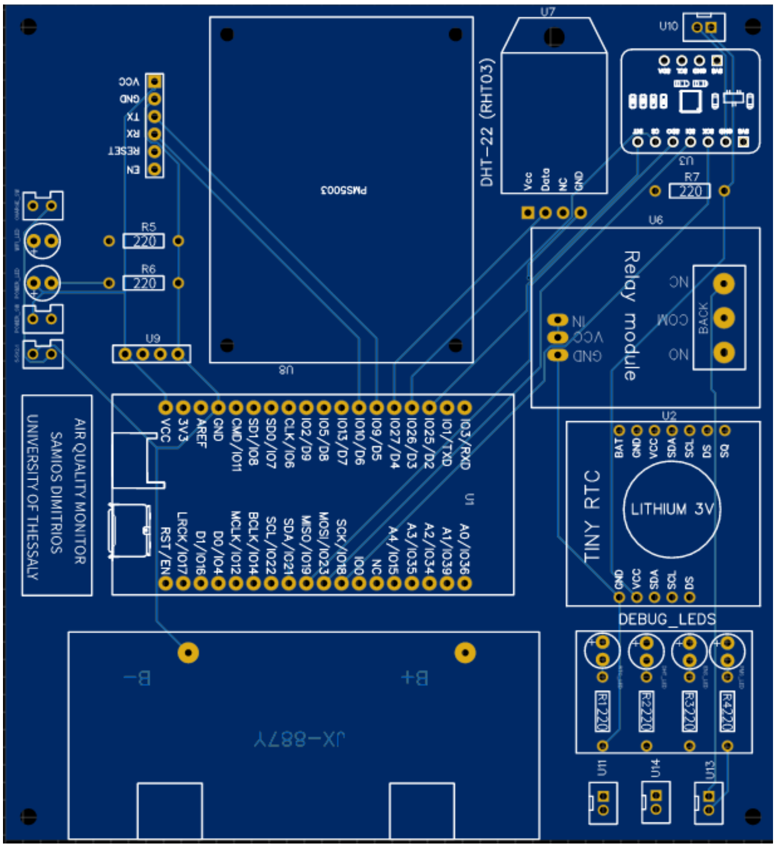


Figure 3.17 Final PCB.

For the actual PCB fabrication, JCLPCB was chosen as the manufacturer. Their platform provided an easy-to-use interface for uploading the zip file containing the Gerber and NC Drill files. JCLPCB offers visual previews and detailed information about the PCB, facilitating the review and confirmation of the design details.

As soon as the PCB specifications were approved, the desired properties, such as the board material and thickness, were chosen. An order was placed at an affordable price. This streamlined process made it convenient to bring the PCB design to life without extensive technical expertise.

3.3 Software Development

The purpose of this chapter is to provide an overview of the software design and implementation across all levels of the integrated system. The coding aspects of the device, the development of the web application, and the way in which these components interact and communicate will be discussed.

3.3.1 ESP32

Arduino

When it comes to programming Arduino devices, the Arduino IDE (Integrated Development Environment) is a powerful tool at your disposal. It simplifies the process of writing code for Arduino boards. It is based on an open-source platform called Processing, which is known for its simplicity and user-friendliness.

A key advantage of the Arduino IDE is its extensive collection of examples and code libraries. Using these resources, you can save a great deal of time and effort by utilizing ready-made solutions for common tasks and functionalities. It is likely that there is already a library available that can assist you in achieving your objectives, whether you are trying to interface with a sensor, control an actuator, or communicate with other devices.

Furthermore, the Arduino IDE provides a user-friendly interface for beginners. With Arduino, users can avoid the complexities associated with C/C++ programming. It eliminates the need to declare function prototypes in header files or deal with intricate compilation details. This will enable you to concentrate on writing the logic for your project using two fundamental functions: setup() and loop(). The setup() function is executed once at the beginning of the program, allowing you to initialize variables, configure pins, and perform any necessary setup tasks. The loop() function, on the other hand, is repeatedly executed after the setup() function. This allows you to define the main logic of your program, such as reading sensor values, making decisions, and controlling outputs.

PlatformIO

In this project, we used PlatformIO, an alternative development environment for programming Arduino devices. This tool provides a number of features and tools that are designed to enhance the development process. The platform allows you to work with a wide range of hardware platforms beyond Arduino, including ESP8266 and ESP32. It features a user-friendly interface, code auto-completion, project management, and debugging features. Also included in PlatformIO is a library manager that simplifies the process of including pre-built libraries in your projects. It integrates seamlessly with popular code editors, such as Visual Studio Code, Atom, and Sublime Text. PlatformIO is a powerful and convenient choice for programming Arduino, offering improved development capabilities and flexibility.

In the course of our project, we greatly benefited from the extensive collection of code libraries available for various sensors. Due to the availability of these libraries, the development of our prototype was accelerated, allowing us to focus on specific functionality without the need to reinvent the wheel.

SPIFFS

The ESP32 includes the Serial Peripheral Interface Flash File System (SPIFFS), which is a lightweight file system designed for use with microcontrollers with Flash memory connected via SPI, such as the ESP32's Flash memory. With the help of an Arduino library, it is possible to upload files directly to the ESP32's file system.

Like a regular file system on a computer, SPIFFS provides simple and limited access to Flash memory. The program supports reading, writing, closing, and deleting files, but does not support directories. As a result, all files are stored in a flat format. SPIFFS is particularly beneficial for creating configuration files, storing permanent data, creating log files instead of microSD cards, and storing web server files such as HTML, CSS, and images.

This implementation utilizes the SPIFFS system for the creation, editing, and permanent storage of a configuration file. The file contains Wi-Fi settings and cloud credentials. In addition to that, it also stores the files associated with the web application itself.

Presentation of the System's Functionality

It has already been mentioned that the IoT device plays a crucial role in the functionality of the implemented system. The device has multiple uses, including monitoring Indoor Air Quality (IAQ), serving as a Wi-Fi access point, hosting a web server for web applications, and transmitting data to the cloud. This section does not provide the Arduino source code for ESP32. However, it does provide an overview of the overall flow and behavior of the sensor system in relation to the sensors/peripherals and web interface. As a reminder, the communication between the ESP32 and its sensors/peripheral devices is implemented using Arduino libraries.

Upon initialization, the IoT device's processing unit performs a series of essential steps. The device initializes the sensors connected to the device and the Real-Time Clock (RTC) module to ensure reliable and accurate data collection. Afterward, the device checks for saved Wi-Fi credentials in persistent memory. In the absence of Wi-Fi credentials, the device operates as a Wi-Fi Access Point, a web server, and a WebSocket server. Users can connect to the device via their web browsers, scan for available networks, and connect to a network using a password if necessary. This initial setup phase allows users to establish a connection and configure the device according to their preferences.

In the event that Wi-Fi credentials are already available, the WebSocket service and web server are started immediately. The web interface of the IoT device can be accessed by multiple devices through the established Wi-Fi network. In addition, the device transmits periodic data to the cloud for storage and analysis.

During the communication between the IoT device and the web application, the device transmits real-time sensor readings. Using the system, users are able to observe current IAQ conditions such as temperature, humidity, particulates, TVOCs, and eCO2 concentrations. Additionally, the user-friendly interface of the device allows users to interact with it and customize its settings according to their preferences.

When a user wishes to terminate the connection, he or she should close the browser tab. In the absence of any connected users, the device stops sending data over a WebSocket to the web application. However, it continues to transmit sensor readings to the cloud, ensuring continuous data storage and accessibility. This allows users to analyze the collected data later, even if they are not actively monitoring the system.

3.3.2 Web Application

The purpose of this section is to describe the implementation of the web interface hosted on the IoT device's web server. It describes the technologies used, design and configuration options, sensor data visualization, optimization and compression techniques, and considerations for user experience and usability.

Technologies Used

The web interface was developed using Vue.js, a JavaScript framework well-known for its interactive capabilities. The choice of Vue.js was based on its flexibility and component-based architecture. To ensure code maintainability, TypeScript, a statically typed superset of JavaScript, was employed to enhance development.

In order to facilitate styling and layout, Bootstrap, a popular framework, was incorporated. This framework provides a wide variety of pre-designed components as well as a responsive grid system that makes it easier to create visually appealing and responsive interfaces. The combination of Bootstrap and Vue.js ensured smooth component integration and consistent styling.

The Vite builder was used to optimize and compress the web interface project. Through this tool, the project files could be efficiently bundled and minified, resulting in an optimized build of index.html, index.js, vendor.js, and index.css.

Design and Configuration

The web interface was designed to provide users with an intuitive and user-friendly experience. In addition to adopting a clean and modern visual aesthetic, an organized layout was adopted to facilitate easy access to and configuration of the settings for IoT devices. Users are able to customize various aspects of the IoT device. By using an intuitive and easy-to-use configuration interface, users were able to change Wi-Fi settings, sensor preferences, and data collection intervals. Consequently, the device could be customized according to the needs of the user.

Sensor Data Visualization

The web interface enabled real-time visualization of sensor data, allowing users to monitor and analyze air quality information in real time. Temperature, humidity, and pollutant levels were displayed as live sensor readings in a user-friendly format. Additionally, users were able to explore interactive charts that displayed trends and patterns over time via the web interface.

Optimization and Compression

The Vite builder was used to optimize and compress the web interface project. The project files had to be bundled and minified in order to reduce their size, as the ESP32 has a limited amount of persistent memory storage. Additionally, these optimizations improved loading speeds and enhanced overall performance, ensuring a smooth user experience. Moreover, compression techniques were employed to reduce the size of JavaScript and CSS files without compromising their functionality or integrity. As a result of these measures, loading times were significantly reduced, particularly on devices with limited bandwidth or processing power.

User Experience and Usability

In designing the web interface, a strong emphasis was placed on user experience and usability. Testing sessions with participants with varying levels of technical expertise were conducted in order to identify potential issues and areas for improvement. These sessions provided insights that were used to refine the interface iteratively, resulting in improved intuitiveness and accessibility for a wide range of users.

3.4 Remote Data Storage and Accessibility

The majority of IoT applications require external data storage, processing, and visualization capabilities. One approach is to create a specialized server specifically for this purpose, either from scratch or by utilizing existing open-source solutions. For instance, Grafana is a popular platform for data analysis and presentation. InfluxDB allows direct storage of time-series data without an additional server. Another option is Firebase, which, when combined with Google's cloud services, can be effective. However, developing such an application that combines multiple technologies takes time, programming expertise, and familiarity with the requirements of each solution. Additionally, building the IoT device code from scratch is necessary.

Considering the focus of the project, it was determined that pursuing such efforts would divert attention from the core objective.

Creating, installing, and managing servers for IoT devices can be a challenging task. Consequently, there has been a significant growth in the market for data storage, processing, and visualization, with numerous companies of various sizes operating in this field. Besides major cloud computing service providers, there are also open-source software solutions available.

Large companies have the advantage of integrating a variety of services (databases, analytics, alarms, computing, machine learning, etc.) into a single platform, which allows the development of a variety of applications. There are numerous examples in this category, including Amazon AWS IoT Core, Google Cloud IoT, Microsoft IoT Hub, IBM Watson, Bosch IoT Suite, and Dell IoT. To utilize these services, however, it often takes time to become familiar with the platforms, complex initial configuration is necessary, and low-level code is necessary to ensure effective communication between IoT devices.

Furthermore, these companies offer ready-made solutions that typically support only encryption-capable devices. Even though this is a desirable and secure feature in today's world, it limits the use of low-cost Arduino devices that utilize 8-bit microcontrollers, which lack the processing power to perform strong encryption protocols. A number of benefits can be derived from these devices, including cost reduction, experimentation, and prototyping.

In order to address these challenges, several smaller companies have developed integrated solutions that are more user-friendly. They provide ready-made libraries and code examples for popular IoT devices, enabling quick prototyping and addressing application development and connectivity issues. Although some solutions are aimed exclusively at hobbyists, others offer professional-grade quality with customizable features.

Some noteworthy solutions that rely fully or heavily on open-source code implementations. While they may provide cloud-based data hosting services, it is important for security and data control to have the option of local or user-controlled server storage.

The Thinger platform is a comprehensive open-source solution that meets the requirements. It also offers features for remote device management and updates, as well as drivers for local server installation. The initial configuration is relatively straightforward, although some time is needed for familiarization, which is brief.

Another solution is Blynk, a user-friendly platform that enables developers to create simple mobile applications for controlling and monitoring IoT devices. By utilizing a drag-and-drop interface, users can design their own custom interfaces without having to be proficient in coding. Blynk offers a wide range of pre-built widgets and functionalities that can be easily incorporated into an app. Developers can easily prototype and deploy Internet of Things projects with Blynk by connecting their devices to the cloud and enabling remote control and data visualization in real time. It is compatible with a wide range of hardware platforms and communication protocols, making it a versatile option for the development of IoT applications.

Similarly, there are platforms such as Things.io, Ubeac.io, and Adafruit IO which are not open source but are highly regarded.

For this project, it was decided to utilize ThingsBoard, which provides an open-source, zero-cost solution without support, as well as a commercial license with support. Communication is based on the well-known MQTT protocol for data transmission and reception. By using ThingsBoard, you can easily collect, process, and visualize data from any IoT device.

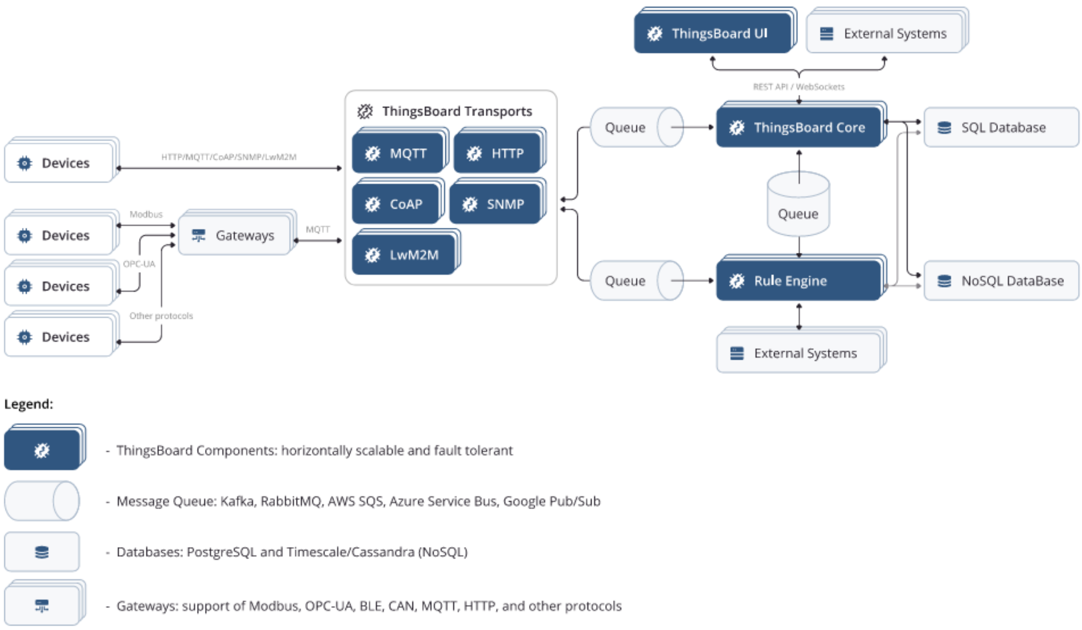


Figure 3.18 ThingsBoard Architecture.

One of its most prominent capabilities is its ability to manage a large number of entities. In this regard, let's consider the concept of a "tenant.". A tenant is an individual or an organization that owns or produces property. In ThingsBoard, these tenants become distinct business units with diverse clients, devices, and assets. Each tenant has the power to manage entities and access the dashboard at will.

A complex rule engine forms the basis of the ThingsBoard system which manages the incoming data messages (Figure 3.18). Each node within the rule engine cluster is assigned a portion of these messages, similar to postmasters sorting incoming mail. This rule engine operates both in shared and isolated modes, providing the flexibility to process messages from multiple tenants or restricting its operations to a specific group of tenants. This facilitates the efficient handling of data.

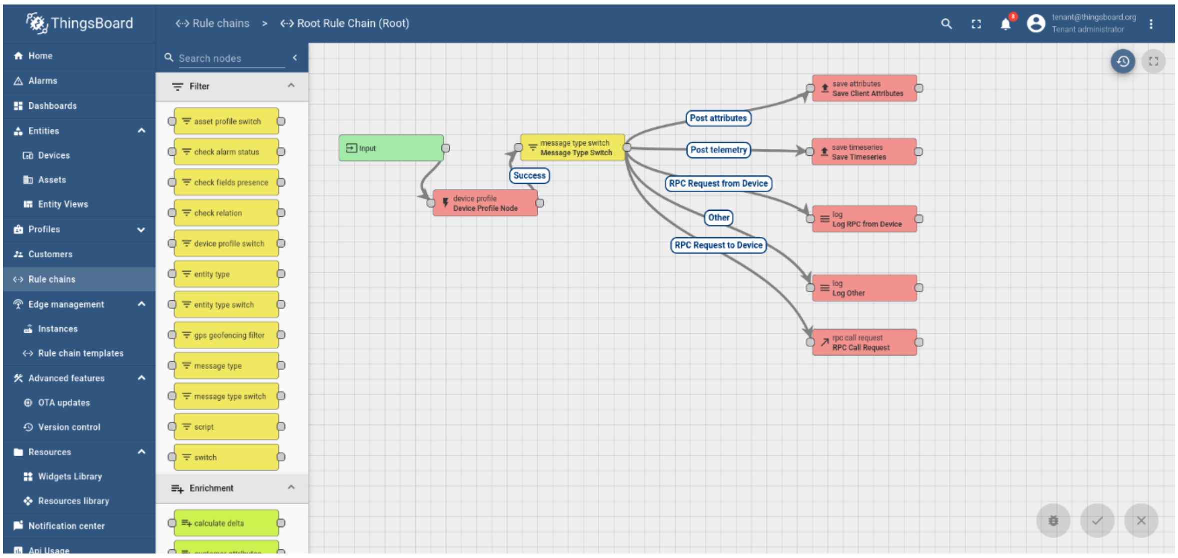


Figure 3.19 ThingsBoard Rule Engine.

Among ThingsBoard's many utilities are the device manager. It facilitates the registration and management of devices while enabling server and client-side monitoring of attributes (Figure 3.19). This feature integrates a complementary Application Programming Interface (API), allowing bi-directional communication between server-side programs and devices.

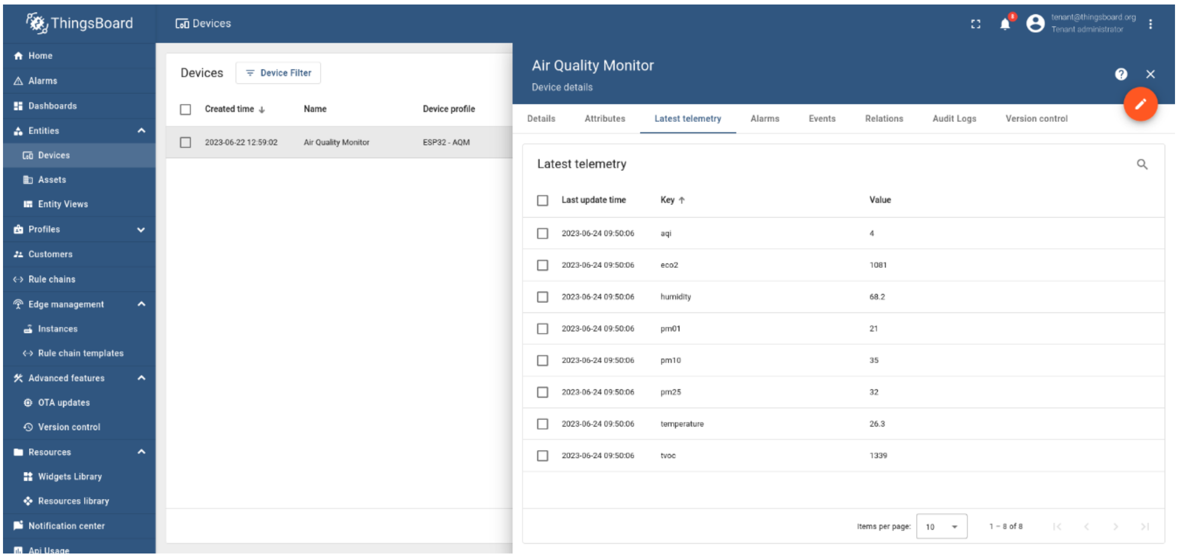


Figure 3.20 ThingsBoard Device Manager.

A cornerstone of ThingsBoard's design is its emphasis on security, which insists on devices interacting with the server displaying credentials. The ThingsBoard provides a secure, yet flexible environment for data exchange by supporting a variety of device credentials and access tokens.

A key component of ThingsBoard's infrastructure is the alarm system. Essentially, it provides users with alerts whenever anomalous conditions occur, such as CO2 readings exceeding a preset limit. By distinguishing alarms according to their origin, start time, and type, the platform ensures live alerts are unique and relevant.

In terms of dashboard design, ThingsBoard allows for the visualization of real-time sensor readings, historical data, charts, and alerts. From Figure 3.20, it is clear that the visualization capabilities are nothing short of extraordinary. The interactive dashboard offers a graphical representation of collected data. With no coding required, you can use control widgets, maps, and built-in charts, and customize every aspect of your dashboard using complex widgets or bespoke bundles.

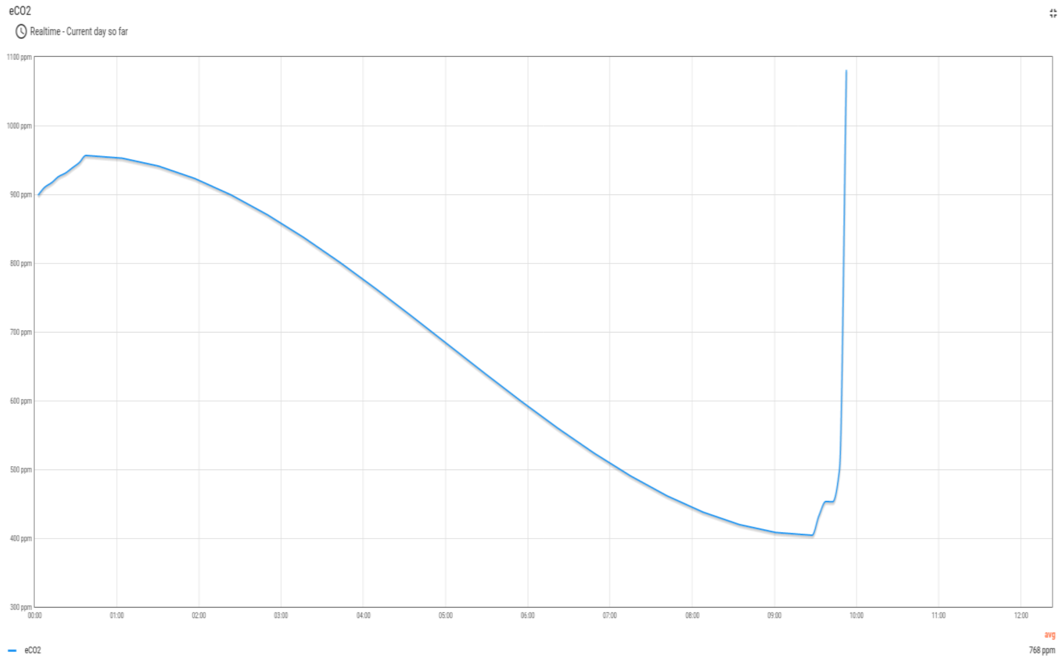


Figure 3.21 ThingsBoard's Line Chart widget.

ThingsBoard's versatility shines through when deployed. Deployments can be performed on bare metal or Kubernetes in both on-premises and cloud environments. As a result, the platform is able to scale horizontally to accommodate over half a million connected devices. The system employs built-in protocols such as MQTT, SNMO, and HTTP for direct device connection, while also employing broader gateways for local network devices.

As part of this project, ThingsBoard was installed on a virtual machine running Ubuntu as the operating system. The installation process was straightforward after following the official guide. Despite the tremendous amount of configuration options, which can easily become overwhelming, ThingsBoard has provided well-structured instructions to help simplify the process. In order to communicate directly between ThingsBoard and the Air Quality Monitor device, MQTT is used. After the installation and configuration were completed successfully, the device started sending data to ThingsBoard. Figure 3.21 illustrates how this data was visualized using interactive dashboards and charts that allowed quick analysis of the data and identification of anomalies.

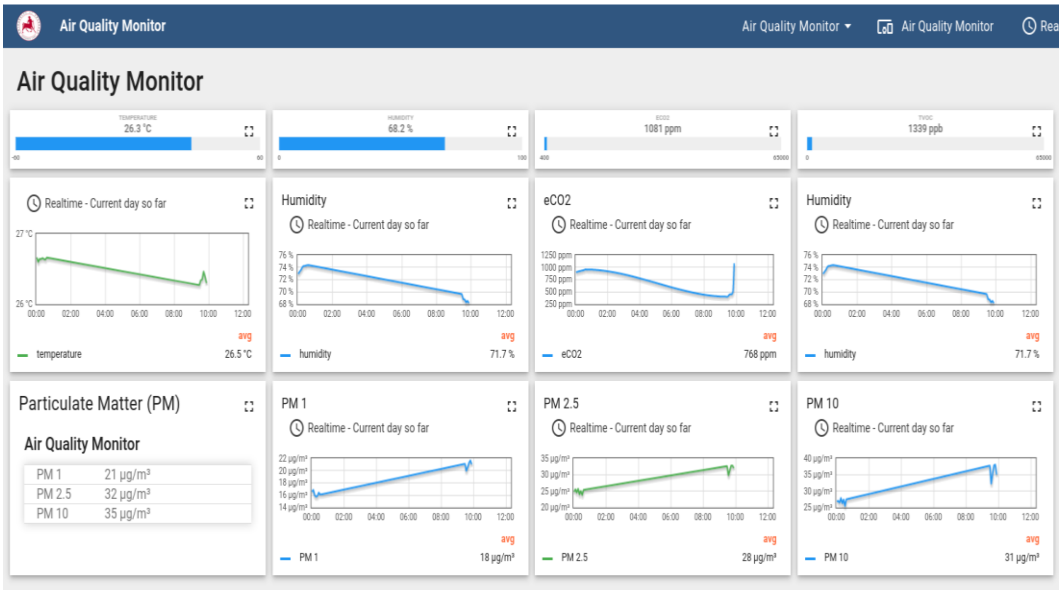


Figure 3.22 Air Quality Monitor Dashboard.

Chapter 4 Results and Discussion

4.1 Data Collection and Monitoring Areas

The measurements were conducted in two residential indoor spaces and one commercial space in the city of Kavala. During the testing period, the temperature in the indoor spaces ranged between 22 and 30 degrees Celsius, providing a comfortable environment. The relative humidity varied from 55% to 85%, indicating a moderate level of moisture in the air.

The first environment examined was situated on the first floor of a building in Kavala's western part. Throughout the testing period, the balcony doors remained open, allowing natural ventilation and fresh air circulation. This space also accommodated two pets, contributing to the overall living environment. Additionally, an ionizer was installed in the primary areas of the house, such as the living room and bedroom, to enhance the air quality. Although there was an energy-efficient fireplace, it was not operational during the testing phase.

The second environment is located on the second floor of a building in the northern part of Kavala. It featured a well-defined separation between the kitchen, dining area, and living room, creating distinct functional zones within the space. Each room had a balcony door that was predominantly closed throughout the day, although occasional natural ventilation was allowed. It's worth noting that the occupants of this space included both traditional smokers and users of electronic cigarettes. This occasionally led to increased pollution levels resulting from indoor smoking activities.

The third environment was situated in a highly central area of Kavala, surrounded by various dining establishments, and experiencing significant car traffic. It served as a technical office, where electronic circuit repairs and mechanical component tasks were carried out. The bustling location contributed to a dynamic and vibrant atmosphere, with numerous people and vehicles passing by throughout the day.

4.2 Data Analysis

In most cases, air pollution increased within 30 seconds of discernible events and most often within five minutes of initiating the activity. Despite the fact that pollutant levels were reduced after the event for some time, the effect lasted for quite some time. The introduction of fresh air into the building through open windows and balconies can help to reduce the concentration of pollutants in the air. In addition, air purifiers can also be used to reduce overall air pollution levels in the home. It is important to note that the device does not have automatic recognition capabilities to identify and associate specific activities with pollutants.

As part of the monitoring process, various activities consistently create pollutants, which can be identified through sensor data.

- Cooking: Cooking activities, especially those involving frying or grilling, release significant amounts of pollutants into the air. Cooking oils, fats, and food particles produce volatile organic compounds (VOCs) and particulate matter (PM).
- Soldering: Soldering electronic components releases hazardous substances, such as lead-based solder fumes and flux emissions. These emissions contain harmful chemicals that can affect indoor air quality if proper ventilation measures are not in place.
- Smoking (Conventional and Electronic Cigarettes): Smoking is a well-known source of indoor air pollution. Both conventional and electronic cigarettes emit volatile organic compounds (VOCs), carbon dioxide ($CO2$), and particulate matter (PM).
- External pollutants: Pollutants from external sources, such as vehicle exhaust and industrial emissions.
- Air fresheners and scented products: Despite their intended purpose, certain air fresheners, scented candles, and other aromatic products release high amounts of volatile organic compounds (VOCs) and carbon dioxide ($CO2$).
- Insect repellents: The use of insect repellents, particularly those in spray or aerosol form, leads to an increase in volatile organic compounds (VOCs).

In addition, it should be noted that rooms with pets have been found to have elevated pollutant levels, which indicates that pet fur increases air pollutants. Furthermore, areas with mold growth and excessive dust accumulation have shown higher levels of pollutant contamination.

In contrast, some activities have shown minimal or momentary changes in pollutant levels:

- Dusting
- Vacuuming
- Showering
- Making espresso coffee
- Washing the dishes

4.3 Illustrative Diagrams for Each Activity

4.3.1 Cooking

Cooking has been found to contribute significantly to indoor air pollution, particularly in terms of particulate matter (PM). Depending on the specific cooking method and ingredients used, the impact of cooking activities on pollutant generation may vary.

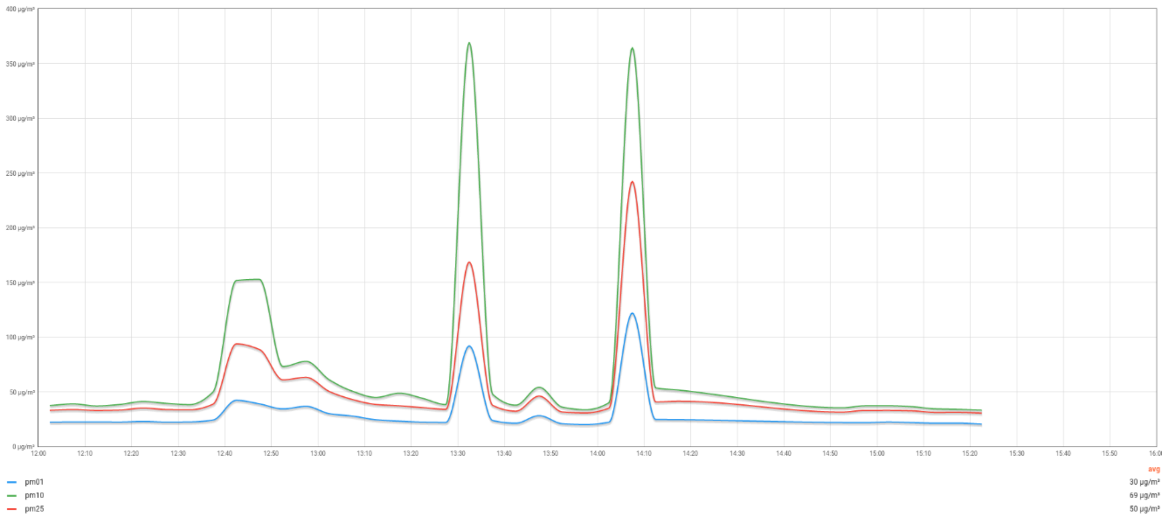


Figure 4.1 PM Pollutants levels during cooking.

According to the data collected, it was found that cooking in an oven generated particle, but this was not consistent across all types of cooking. As shown in Figure 4.1, during vegetable roasting, there was a slight increase in pollutants between 12:00 and 12:30.

Between 12:30 and 13:00, however, PM pollutants increased more pronouncedly during meat roasting. Considering this, different cooking processes and ingredients may have varying effects on pollutant emissions.

Furthermore, we found that frying activities contributed significantly to the pollution of indoor air. During the period between 13:25 and 14:15, pollution levels increased significantly. As a result, it is essential that windows and range hoods be opened while cooking to increase ventilation and help remove pollution.

4.3.2 Air fresheners

In Figure 4.2 and Figure 4.3, air fresheners and scented products contribute significantly to the increase in CO2 and VOC levels. During the introduction of these products into the room at 15:00, the concentration of CO2 and VOCs significantly increased.

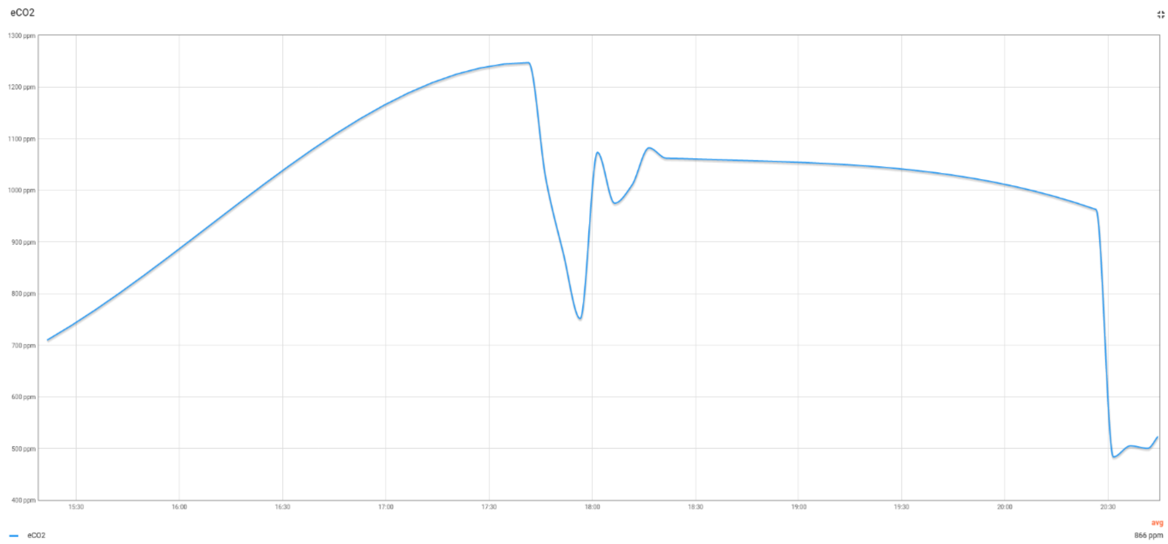


Figure 4.2 Air fresheners eCO2 levels.

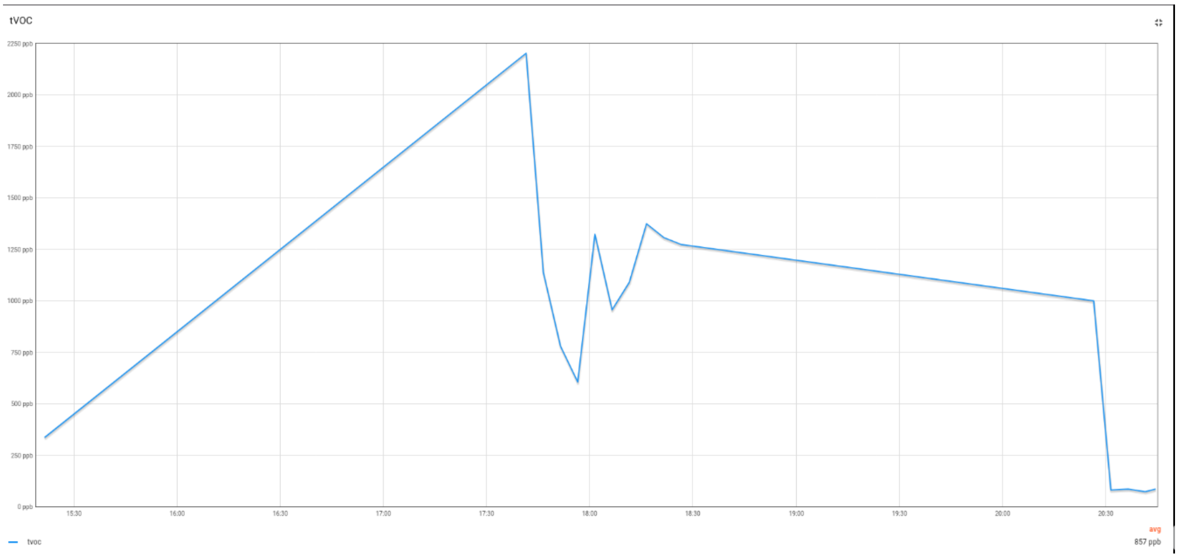


Figure 4.3 Air fresheners VOC levels.

Despite this, positive steps were taken at 17:40 to improve the air quality. By opening the windows, fresh air entered the room, while scented products were removed. The effectiveness of ventilation in reducing indoor pollutants was demonstrated by a decrease in CO2 and VOC levels because of this intervention.

Around 18:00, the windows were closed, and the air conditioning system was turned on. As air conditioning systems have varying levels of filtration and ventilation, this change in environmental conditions has influenced pollutant levels. Finally, at approximately 20:30, the fresheners were turned off, and the windows were reopened. As a result of this action, pollutants have been mitigated and air exchange has been improved.

The impact of air fresheners and scented products on PM levels was found to be negligible, as shown in Figure 4.4. During the timeframe of 15:00 to 20:30, no significant changes in PM concentrations were observed in relation to the introduction, removal, or operation of air fresheners and scented products.

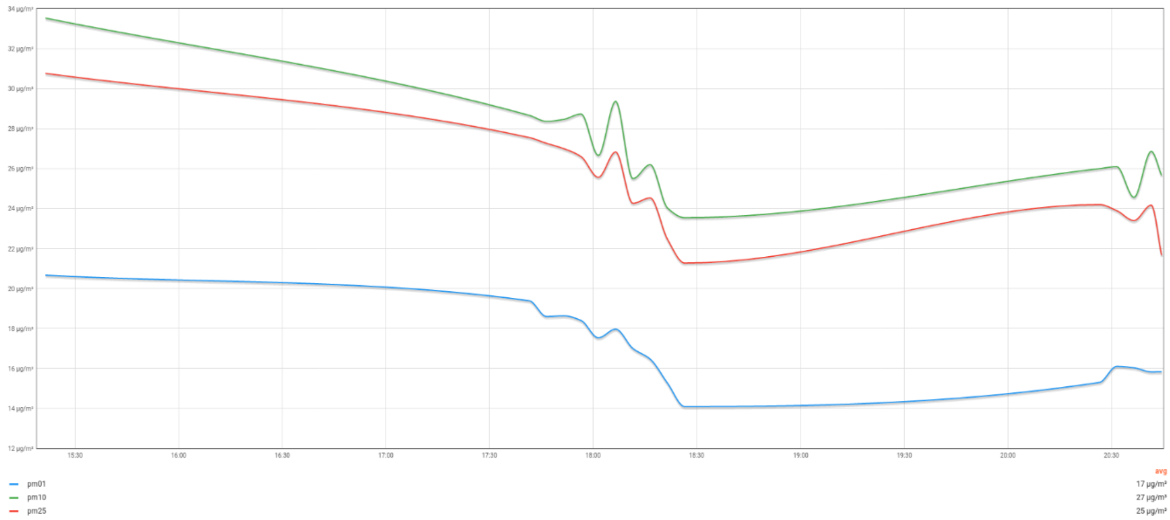


Figure 4.4 Air fresheners PM levels.

4.3.3 Smoking

Whether conventional cigarettes or electronic cigarettes, is known to contribute to indoor air pollution. When a person smokes, significant amounts of PM pollutants are released into the air.

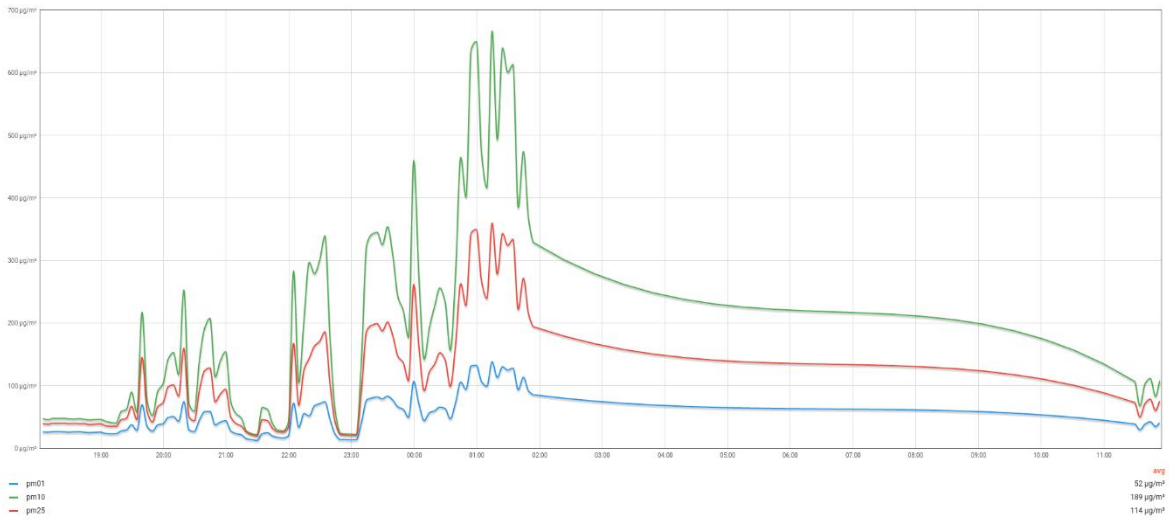


Figure 4.5 PM levels during smoking.

As can be seen in Figure 4.5, pollutant levels increase during smoking activity. As more people started smoking, the levels increased. Despite this, adequate ventilation, such as opening windows or using air purifiers, reduces pollutant levels. Notably, during the observation period, a significant reduction in pollutant levels can be observed between 21:00-22:00 and 23:00 when the windows were open.

Furthermore, it is worth noting that the levels of CO_2 were also elevated. However, it is important to clarify that the increase in CO_2 shown in figure 4.6 is not directly attributed to smoking, but rather to the use of insect repellents.

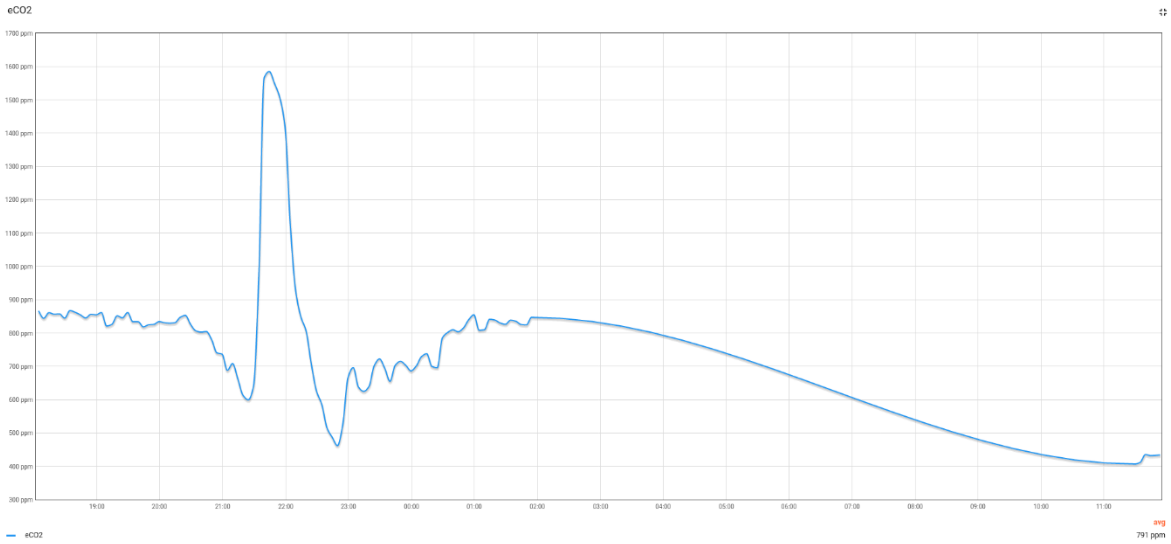


Figure 4.6 CO2 levels during smoking.

4.3.4 Soldering

Soldering electrical components produce significant PM pollutants, particularly those larger than PM2.5 (Figure 4.7). In contrast to PM10, which exhibits a noticeable doubling in concentration, PM1.0 and PM2.5 appear to be less subject to variation. Nevertheless, it should be noted that the sensor's limited sensitivity to pollutants larger than PM2.5, as reported in the literature, suggests that their actual quantity may be higher.

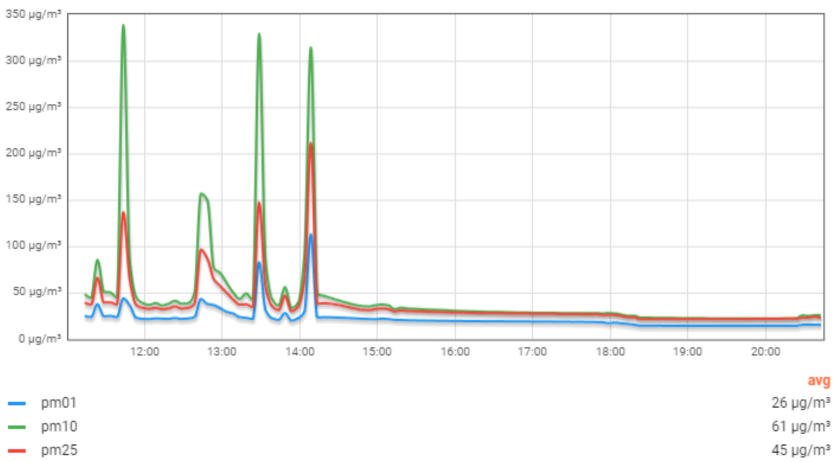


Figure 4.7 PM levels during soldering.

The soldering activities were conducted at approximately a distance of 2 meters from the device. Furthermore, the presence of professional ventilation systems mitigated the effects of the pollutants. According to the results, the pollutants dissipated relatively quickly after the soldering event, indicating that the ventilation system was effective in reducing their persistence in the environment.

4.3.5 Candles

Figures 4.8 and 4.9 illustrate the impact of burning candles on indoor air quality, specifically in relation to CO2 and PM pollutants. Contrary to the findings in the literature, no noticeable increase in VOC levels was observed during the specified time window, as shown in Figure 4.10.

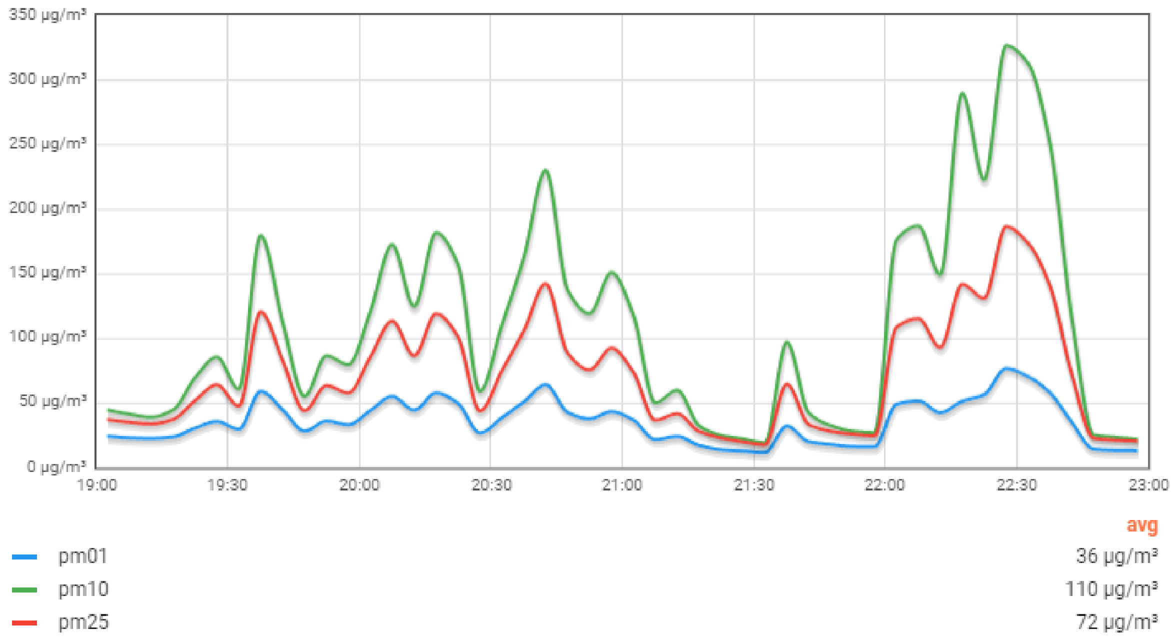


Figure 4.8 Burning candles PM pollutants.

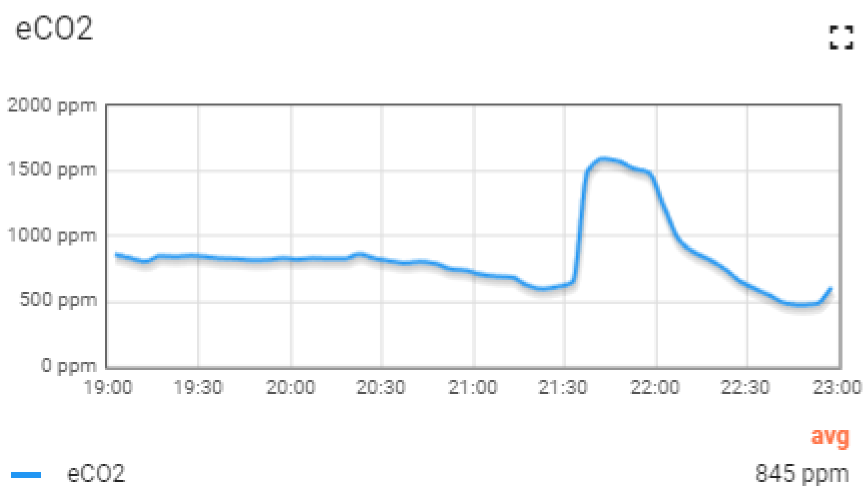


Figure 4.9 Burning candles eCO2 pollutants.

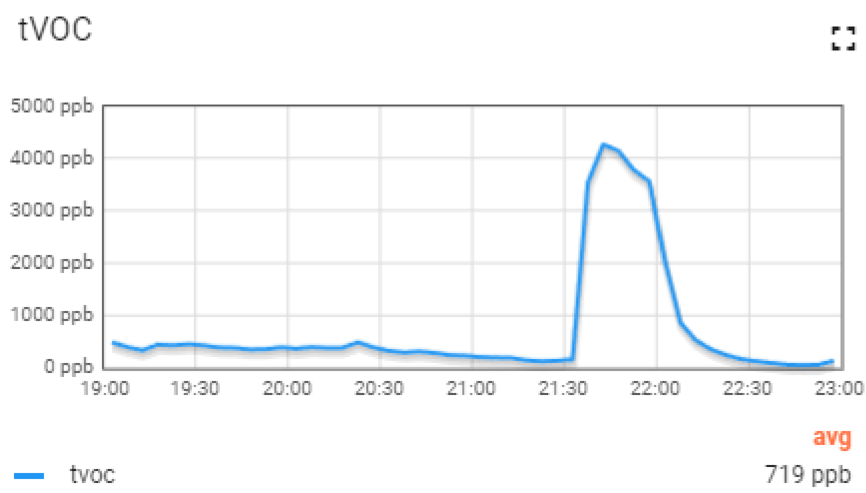


Figure 4.10 Burning candles tVOC pollutants.

However, once the windows were opened at 21:00, the PM levels quickly returned to normal, while the CO2 levels remained elevated. An interesting observation occurred at 21:30 when the candles were blown out, resulting in a temporary spike in both CO2 and VOC levels. This suggests that while candles primarily contribute to CO2 and PM emissions, the act of extinguishing them can release additional pollutants.

Chapter 5 Conclusion and Future Work

5.1 Summary and Conclusion

This study contributed to the development and deployment of a low-cost IoT-based air quality monitoring system. With the assistance of IoT technology, we have been able to gather invaluable environmental data through this project. This system demonstrated reliable performance across both residential and office environments, illustrating the variations in indoor air quality in these environments.

It is estimated that the device will cost approximately 40 euros to produce, which is significantly less than those discussed in the literature review. This cost-effectiveness allows for the establishment of a more widespread network of indoor air quality monitors, previously impossible due to high costs. In the evaluation of the various components, the PMS5003 sensor stood out due to its ease of use and consistent, reliable results.

The IoT device we developed is not without its limitations, despite its effectiveness and its advantages over existing solutions, such as the ability to update data more frequently and the ability to customize it more. The absolute values reported by the sensors may be uncertain, particularly in the absence of calibration with a certified reference sensor. When dealing with low absolute values, this margin of error becomes more significant.

Furthermore, an effective system that is capable of detecting and addressing pollution incidents in a timely manner cannot be overstated. When the problem is detected immediately, the occupants of the affected environment can receive prompt notification, enabling them to take the necessary corrective action. By adopting this proactive approach, the potential health risks associated with pollutant exposure can be effectively minimized.

Nevertheless, relying solely on recorded particulate matter curves may make it more difficult to identify specific pollution events precisely. In order to gain a comprehensive understanding of pollution sources and causes, additional analysis and data integration may be required. Other environmental factors, such as the presence of specific chemicals or pollutants, as well as temperature and humidity, should also be considered. Additionally, it may be necessary to consider factors related to human activities within the indoor environment.

5.2 Future Work

Further development and exploration are possible for this research. An examination of advanced methods for analyzing the collected data offers an exciting potential direction for future research. For example, utilizing machine learning algorithms could make it possible to predict air quality trends based on historical data.

In addition to the existing sensors, additional sensors could be added so that the device can detect a wider range of pollutants. There has been discussion about the possibility of incorporating sensors specific to formaldehyde, one of the most common indoor air pollutants. Additionally, combining the data collected indoors with those collected outdoors might provide a more comprehensive understanding of the dynamics of air quality.

The device has considerable potential for integrating user feedback mechanisms. It would be very beneficial for the device to be capable of alerting users of sudden changes in air quality or suggesting improvements for air quality based on the collected data.

It may be beneficial to replace the ESP32 with an ESP8266 to improve the cost-effectiveness and energy efficiency of the system. As a result of this modification, additional components, such as a GPS module, may be added to provide precise geolocation of measurements.

In order to enhance scalability and streamline data management, it would be advantageous to construct a dedicated cloud platform for the system. Lastly, it would be beneficial to refine the user interface to enhance the overall user experience. It would be helpful if the system could provide clearer visual representation and easier access to the results.

This study highlights the potential role of IoT in monitoring indoor air quality. Further research in this area may lead to the development of more robust and effective solutions that contribute to healthier and safer indoor environments.

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Appendices

Appendix A: Source code

The source code for ESP32, the Web App, and the Nextion display can be accessed on the following GitHub repository:

https://github.com/dsamios/AirQualityMonitor

Appendix B: External libraries

In addition to the built-in libraries of the Arduino platform, the following external libraries were used:

- me-no-dev/AsyncTCP@^1.1.1
- me-no-dev/ESP Async WebServer@^1.2.3
- links2004/WebSockets@^2.3.7
- bblanchon/ArduinoJson@^6.21.2
- adafruit/Adafruit Unified Sensor@^1.1.9
- adafruit/DHT sensor library@^1.4.4
- beegee-tokyo/DHT sensor library for ESPx@^1.19
- adafruit/RTClib@^2.1.1
- dfrobot/DFRobot_ENS160@^1.0.1
- fu-hsi/PMS Library@^1.1.0
- avaldebe/PMSerial@^1.2.0
- adafruit/Adafruit PM25 AQI Sensor@^1.0.6
- majenkolibraries/Blinker@^1.0.3
- plerup/EspSoftwareSerial@^8.0.3
- knolleary/PubSubClient@^2.8