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Wildfire detection based on IoT technology

Daniel Filipe Gonçalves Freira

Master in Computer Engineering

Supervisor:
PhD Carlos Eduardo Dias Coutinho, Assistant Professor
Iscte-IUL

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TECNOLOGIAS
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Department of Information Science and Technology (DCTI)

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To my grandfather, whose memory inspires me every day. This work is a testament to the values and resilience you instilled in me. You are deeply missed and forever remembered.

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I would like to express my heartfelt gratitude to everyone whose support made the completion of this work possible.

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Resumo

Os incêndios florestais são uma preocupação global devido à sua crescente gravidade e frequência, resultando em perdas económicas, ambientais e humanas. Estes eventos afetam principalmente áreas rurais com elevada acumulação de matéria orgânica e vigilância inadequada. Os métodos tradicionais de deteção de incêndios baseiam-se em sensores que detetam calor, partículas de fumo, gases específicos e emissões radiativas. A tecnologia da Internet das Coisas (IoT) oferece uma solução promissora para a deteção remota de incêndios florestais, proporcionando sensores de longa duração e baixo consumo de energia que operam de forma autónoma.

Apesar dos desafios em garantir conectividade em áreas remotas, tecnologias como LoRaWAN permitem uma comunicação de longo alcance e eficiente em termos de energia a um custo reduzido. Recorrendo as tecnologias IoT e LoRaWAN, é possível desenvolver um sistema de monitorização de incêndios florestais que oferece vigilância em tempo real e alertas antecipados às autoridades, melhorando as capacidades de resposta. Este projeto tem como objetivo conceptualizar, projetar e desenvolver um sistema baseado em IoT, de baixo custo e eficiente em termos de energéticos, para a uma deteção prévia de incêndios florestais.

Palavras-chave: Deteção de Incêndios, IoT, LoRaWAN, Node-RED

Abstract

Wildfires are a global concern due to their increasing severity and frequency, resulting in economic, environmental, and human losses. These events primarily affect rural areas with high organic matter accumulation and inadequate surveillance. Traditional fire detection methods rely on sensors that detect heat, smoke particles, specific gases, and radiative emissions. Internet of Things (IoT) technology offers a promising solution for remote wildfire detection by providing long-lasting, low-power sensors that operate autonomously.

Despite challenges in ensuring connectivity in remote areas, technologies like LoRaWAN enable energy-efficient, long-range communication at a low cost. By leveraging IoT and LoRaWAN technologies, a wildfire monitoring system can be developed to provide real-time surveillance and early warnings to authorities, improving response time capabilities. This paper aims to conceptualize, design, and develop a cost-effective, energy-efficient IoT-based system for early wildfire detection.

Keywords: Wildfires Detection, IoT, LoRaWAN, Node-RED

Index

Index of Figures

Table of Acronyms

$\mu g/m^3$ - micrograms per cubic meter

ASA - Acrylonitrile Styrene Acrylate

BL - Battery Life

CH4 – Methane

CO2 - Carbon Dioxide

CO - Carbon Monoxide

DPC - Daily Power Consumption

ED - Energy Deficit

GHz - Gigahertz

I2C - inter-integrated circuit

IoT - Internet of Things

IEEE - Institute of Electrical and Electronics Engineers

km - Kilometer

Li-Po - Lithium polymer

MHz - Megahertz

MODIS - Moderate Resolution Imaging Spectroradiometer

mAh - milliAmpere-hour

mW - milliWatts

NO2 - Nitrogen Dioxide

PM2.5 - particulate matter with a diameter of 2.5 micrometers or smaller

PM10 - particulate matter with a diameter of 10 micrometers or smaller

ppm - parts per million

Ptotal - Total Power

RH - Relative Humidity

RPI - Required Power input

RPL - Routing Protocol for Low-Power and Lossy Networks

SPI - Solar Power Input

SLR - Systematic Literature Review

TTN - The Things Network

UAVs - Unmanned Aerial Vehicles

UI - User Interface

UV - Ultraviolet

VIIRS - Visible Infrared Imaging Radiometer Suite

VOCs - Volatile Organic Compounds

W - Watt

Wh - Watt-hour

WHO - World Health Organization

WSNs - Wireless Sensor Networks

CHAPTER 1

Introduction

Wildfires have become a concerning global issue with their increase in severity and frequency. These global events not only ruin our landscapes but also lead to massive economic and environmental impacts. Tragically, they often lead to the destruction of people's properties and the loss of lives, be the property owners or the authorities combating the flames [1]. These occurrences are most common in the countryside with high accumulation of organic matter areas where surveillance is insufficient or nonexistent [2].

Traditionally fires have been detected by heat, presence of smoke particles and certain gases, and radiative emissions such as Infrared light [3]. The sensors used in these detectors are mainly used in residential and commercial areas where electricity is easily accessible, and communication infrastructure is present.

Internet of Things (IoT) technology can provide a solution to remote sensor challenges by offering devices, sensors capable of long longevity with relative low power necessities and capable of long-range communication. IoT technology can be described as a network of smart devices that share information without human interaction. IoT has proven effective in various applications such as home automation, healthcare, transportation, agriculture and most relevant to this project, environment monitoring. This technology can be powered by small batteries and is extremely power efficient, allowing the deployment to remote locations [4], [5].

Some challenges still arise with connectivity. Remote areas have difficult access and might not have the necessary network infrastructure. Connectivity through mobile networks might be unreliable or nonexistent, its power requirements and service costs are high. LoRaWAN is used to combat these problems, devices are energy efficient, capable of long-range communication and of low acquisition cost [6].

By leveraging these technologies, a wildfire system could potentially monitor large areas in real-time and provide early warnings by assessing environmental conditions to the respective authorities.

While some investigations have been conducted on this topic, it's still a relevant area to study [4], [6]. Sensor technology is continuously advancing and more cost-effective, enabling further research. This paper's aim is to conceptualize, design and develop an IoT system with relatively low cost and energy efficient to improve early fire detection.

1.1. Research Methodology

This project adopts a hybrid research methodology that integrates a Systematic Literature Review (SLR) with Experimental Research to study and develop an Internet of Things (IoT) solution for wildfire detection.

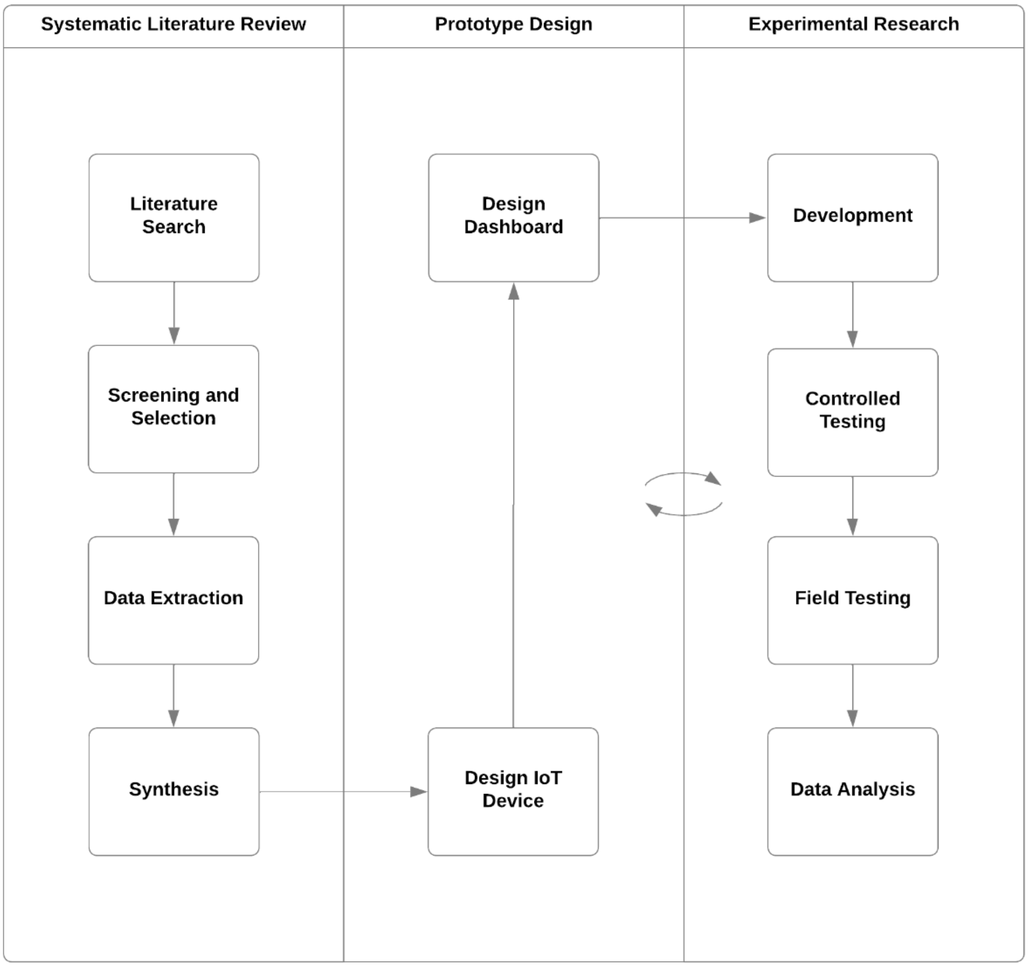

Figure 1.1 - Research Methodology Flowchart

Figure 1.1 represents a flowchart of the previously described research methodology process. Initially the research starts with the SLR to gather, analyze and synthesize existing literature on IoT technology, sensors, LoRa technology, wildfire emissions, IoT middleware platforms and energy efficiency. Various search engines were used such as, Google Scholar, JSTOR, IEEE Xplore, ScienceDirect with the search keywords: “IoT”, “Wildfire”, “Node Red", “LoRa” and “Fire detection”; out of 30 works screened, 18 were selected. This phase is presented in Chapter 2, which will identify key technologies, understand their effectiveness, and find research gaps and challenges with the current reality.

With the comprehension derived from the SLR phase, a Prototype Design phase will start with the design of an IoT Device and a dashboard to report its data. This involves the selection of the necessary electronic components such as the microcontroller and sensors, the modeling of an enclosure for outdoor use, and the conception of the dashboard panels and graphic components. Sections 3.5 and 3.6 will cover this process.

The last phase will focus on experimental research involving the construction and iterative testing of the prototype. It starts with 3D printing the enclosure and verifying for model imperfections, assembling the electronic components, programming the microcontroller and dashboard functionality (As seen in section 3.5.1). Lastly in chapter 4, a closed controlled test will be executed to assess basic functionality and field tests to evaluate its performance in more realistic conditions.

1.2. Research Questions and Hypotheses

Two research questions arise with this research project, and were identified as follows:

- **RQ1:** How can IoT technology be used to improve the detection of wildfires?
- **RQ2:** How would the connectivity and communication between IoT devices be accomplished?

In order to provide an attempt to respond to these research questions, a set of hypotheses were formulated, in this case two for each research question:

- **RQ1_H1:** The creation of a self-sustainable and low-cost IoT device with various sensors may help in assessing wildfire occurrences.
- **RQ1_H2:** The creation of a mesh network of IoT devices may assist in the triangulation of wildfire location.
- **RQ2_H1:** The usage of LoRaWAN Gateways may attain and improve the connectivity and communication of IoT devices (Nodes).
- **RQ2_H2:** The creation of a dashboard to report the data on devices may improve communication of that data to the responsible authorities.

1.3. Document Map

Chapter 1 introduces the theme and motivations.

Chapter 2 presents a Literature Review on the topics researched.

Chapter 3 presents the architecture of the proposed solution.

Chapter 4 showcases a controlled test and its results.

And finally, Chapter 5 presents the Conclusions and Future Work.

CHAPTER 2

Literature Review

This project involves different fields of expertise. The current section reviews relevant studies published in fields such as wildfires emissions and behavior, traditional fire detection, IoT and Sensors, Middleware platforms and Lora Technology.

2.1. Wildfires

By definition, a wildfire is (Cambridge Dictionary, n.d.) "a fire that is burning strongly and out of control on an area of grass or bushes in the countryside".

The impacts of this phenomenon are vast, and it's most felt on biodiversity degradation, destruction of natural resources and agriculture structures, and the negative impact on climate change through the emissions of greenhouse gases like CO_2 (Carbon dioxide), CO (Carbon monoxide) and CH_4 (Methane). The destruction of residential, agriculture areas and firefighting efforts lead to large economic impacts. In the year of 2023, Portugal incurred a cost of 377.2 million euros due to wildfires [7].

Wildfires are generated by a combination of factors, those being ignition, drought, continuous fuels and suitable weather. The conclusions of [2] indicate that fire occurrence is determined by the frequency of which of these thresholds are crossed and its effects are largely influenced by climate change and human activity.

2.1.1. Atmospheric composition and climate

Fires, particularly those resulting from biomass burning, are sources of gas emissions that impact air quality. The primary gaseous emissions include CO_2, CO, and Volatile Organic Compounds (VOCs), with their concentrations varying from most to least abundant. CO_2 is the most abundant gas, typically comprising about 90% to 95% of the emissions, followed by CO, which makes up approximately 5% to 10% [8].

Although these gases are indicative of an active fire, ambient temperature and relative humidity are crucial factors in assessing fire-prone conditions. Higher temperatures reduce the moisture content in vegetation, improving its flammability, while lower relative humidity accelerates the drying process of vegetation. These two variables are essential for predicting the risk of fire occurrence [2], [8].

2.2. Traditional Methods of Wildfire Detection

2.2.1. Early Warning Systems

Early warning systems are important resources to provide timely response and mitigation to fire occurrences. These systems typically use a combination of technologies, including satellite imaging, ground sensors, and aerial surveillance, to detect and monitor wildfires in real-time.

Advanced systems integrate machine learning algorithms to enhance detection accuracy, reduce false alarms, and provide predictive analytics for potential fire outbreaks. Key components of these systems include the collection of environmental data, real-time analysis, and dissemination of alerts to relevant authorities and the public. The effectiveness of early warning systems is largely dependent on the integration of multiple data sources and the rapid processing of information to trigger alerts [9].

2.2.2. Satellite Imaging

Satellite imaging has been used for wildfire detection due to its ability to cover large geographic areas. Satellite systems like MODIS and VIIRS provide data for detecting and monitoring wildfires. MODIS, aboard NASA's Terra and Aqua satellites, offers a revisit time of 1-2 days and captures data in multiple spectral bands, which identifies thermal deviations associated with wildfires.

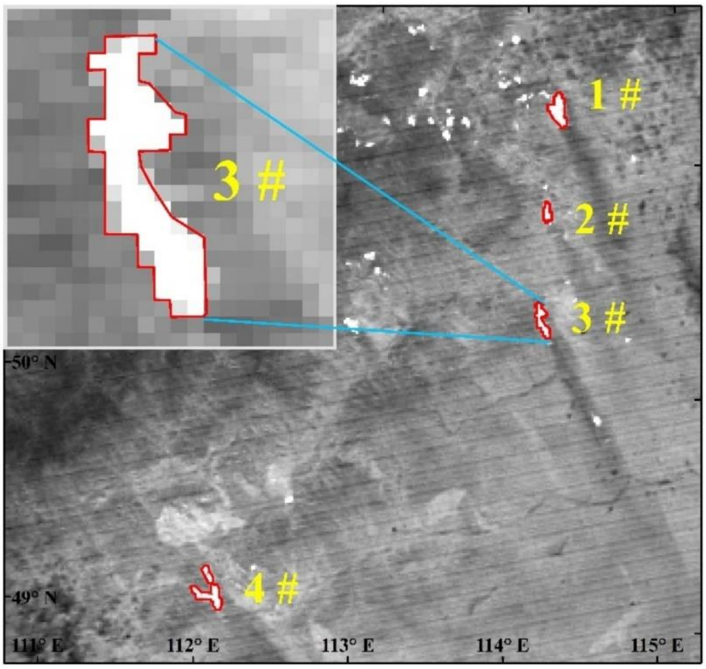

Figure 2.1 – Burned are from MODIS band 21

Geostationary satellites like GOES-16 offer high temporal resolution, providing updates every 15 minutes, but with lower spatial resolution compared to polar-orbiting satellites. Recent advances include the use of CubeSats, which provide improved temporal resolution and cost-effectiveness. However, their data transmission capabilities remain an issue due to its inability to send large amounts of data- [9], [10].

2.2.3. Lookout Towers and Human Patrols

Figure 2.2 – Serra da Talhadas Lookout Tower, Portugal

Lookout towers and human patrols are among the oldest methods for wildfire detection. These methods rely on human observers stationed at strategic points, typically in elevated locations, to visually scan for signs of smoke or fire. While cost-effective and providing real-time data, these methods are limited by human error, the physical range of visibility, and the inability to operate effectively during night or in adverse weather conditions. Despite these limitations, lookout towers and human patrols remain an important component of wildfire detection, especially in remote areas where modern technology may not be available [4], [9].

2.2.4. Aerial Surveillance

Aerial surveillance involves the use of manned or unmanned aircraft equipped with cameras and other sensors to detect wildfires. Early aerial detection efforts began in the 1920s and have evolved significantly with the introduction of infrared imaging, which allows for the detection of fires even through thick smoke.

Modern aerial surveillance often employs Unmanned Aerial Vehicles (UAVs), which provide flexibility and can cover areas that are difficult or dangerous for manned aircraft. However, UAVs are limited by weather conditions and flight time. Aerial surveillance is particularly valuable for detecting fires in their early stages, especially in remote or inaccessible areas [4], [9].

2.2.5. Ground Sensors

Thermal cameras and gas sensors are increasingly being used for wildfire detection. These sensors can detect the thermal signatures of fires or the presence of smoke and other combustion-related gases. Ground sensors are highly effective in providing localized data with high accuracy and can be deployed in large networks to cover extensive areas. However, the effectiveness of ground sensors is limited by the need for a dense network to ensure comprehensive coverage, which can be costly and logistically challenging. Despite this, ground sensors play a crucial role in early detection, especially when integrated into larger, multi-modal detection systems [3], [4], [9].

2.3. IoT Technology and Its Applications

2.3.1. Definition and Scope of IoT

IoT is characterized by the interconnectivity of various devices, sensors, and systems through private or public networks, enabling them to collect, exchange, and act on data without human intervention. The architecture of IoT systems generally includes layers such as the physical layer (sensors and devices), the middle layer (cloud infrastructure for services like storage and event management), and the application layer (user interfaces and applications). These systems are designed to operate autonomously, performing tasks like data collection and communication with minimal human input [4], [11].

2.3.2. Air Quality Monitoring

IoT-based air quality monitoring systems are commonly used to measure and manage air pollution in urban areas. These systems typically consist of low-cost sensors that monitor pollutants such as particulate matter (PM2.5, PM10), nitrogen dioxide (NO_2), CO, and CO_2. The data collected by these sensors is transmitted to a central platform where it is analyzed and compared against air quality standards [12].

For instance, PM2.5 sensors can detect fine particulate matter with diameters of 2.5 micrometers or smaller, which can pose significant health risks. Thresholds for PM2.5 often follow guidelines from organizations like the World Health Organization (WHO), where a 24-hour average concentration of 15 $\mu g/m^3$ is considered the recommended limit for safe air quality [13].

2.4. IoT-based Wildfire Detection Systems

2.4.1. Wireless Sensor Networks (WSNs)

Wireless Sensor Networks (WSNs) are integral to IoT-based wildfire detection systems. These networks consist of distributed sensor nodes that communicate wirelessly to monitor environmental conditions such as temperature, humidity, and gas concentrations. WSNs can detect early signs of wildfires and provide real-time data to authorities. The typical communication range for WSN nodes is 100 to 300 meters in dense forests, and up to 1 kilometer in open areas [6].

2.4.2. LoRa Technology

LoRa technology is particularly well-suited for IoT applications in wildfire detection due to its long-range communication capabilities and low power consumption. LoRa operates in the sub-GHz frequency bands (typically 868 MHz in Europe) and can achieve large communication ranges. A study achieved up to ~30 km, although only 62% of the packets sent were received from the station 30km away [5].

LoRa's low data rate (0.3 to 50 kbps) is sufficient for transmitting sensor data, making it ideal for large-scale deployments where power efficiency and range are critical. The technology supports a star-of-stars topology, where end devices communicate with gateways that relay the data to a central server. This architecture reduces the energy consumption of sensor nodes, prolonging their battery life [14].

The Things Network (TTN) is a global, community-driven LoraWAN network that provides a free and open infrastructure for IoT devices. It offers great coverage due to its large community; its gateways are relatively inexpensive and it has an active community and well documented APIs making it a great solution for prototyping.

2.4.3. CO2 and CO Emission Monitoring

Gas sensors are important components of IoT-based wildfire detection systems, helping the remote monitoring of fire-prone areas and providing real-time data for the detection of early fire. By measuring specific gases released during combustion, such as CO_2 and carbon CO, the two most abundant gases, these sensors identify and respond to wildfires before they escalate [8].

CO_2 sensors are particularly useful in detecting active fires. They measure CO_2 concentrations in parts per million (ppm), typically within a range of 350 to 10,000 ppm. During combustion of combustible forest materials, CO_2 levels from the first ~300 seconds may vary from 20 to 220 ppm, which could trigger alerts and provide valuable data for further analysis and decision-making [15].

Similarly, CO sensors can detect carbon monoxide concentrations within a range of 0 to 1,000 ppm. Alarm thresholds are usually set at 10 ppm to initiate early warning alerts, allowing for a swift response to potential fire hazards [3].

In addition to their role in fire detection, monitoring CO_2 and CO emissions during wildfires is essential for assessing the environmental impact.

2.4.4. Node-RED and Middleware Platforms

Middleware platforms in IoT provide the necessary infrastructure to connect and manage communication between IoT devices and applications. These platforms support device integration, data processing, and protocol management, making it easier to deploy and manage IoT systems [16].

Node-RED is widely used in IoT-based wildfire detection systems for its ability to integrate various sensors and communication protocols into a cohesive system. Middleware platforms like Node-RED allow for the rapid development of data flows, enabling the real-time processing and visualization of sensor data. In a wildfire detection system, Node-RED can be used to manage data streams from multiple sensor nodes, apply threshold-based logic to detect anomalies, and trigger alerts that notify authorities [14], [17].

2.4.5. Similar Projects

Similar projects have demonstrated the effectiveness of IoT-based wildfire detection systems. For instance, a project in Portugal involved the deployment of a wireless sensor network for forest fire detection, using IEEE 802.15.4 standard-compliant devices. The system utilized Contiki OS and the RPL routing protocol to ensure robust communication in a forested environment. The project demonstrated that early detection and real-time data collection could improve the response time to wildfires [6].

Another project focused on the deployment of LoRa-based gas sensors for wildfire detection. The study showed that LoRa's long-range communication capabilities made it possible to cover a radius of 1.1km with relatively few sensor nodes, reducing costs and complexity. The system was able to detect peak CO_2 concentrations corresponding to work communal hours, indicative that it could detect presence of fire.[18].

CHAPTER 3

Project Development

The proposed solution for this project leverages IoT technology to create an efficient, low-cost, and sustainable system. The core of this system involves building a sensor array composed of various low-cost sensors capable of detecting critical environmental parameters, including CO, CO2, relative humidity, temperature, and PM2.5. These sensors will be deployed in strategic locations and connected via a LoRaWAN network for its long-range capabilities and low-power requirements. TTN will be used for data transmission.

To ensure continuous operation in off-grid areas, the sensor nodes will be powered by a solar panel and rechargeable Li-Po battery, allowing for self-sustainability.

The collected data will be processed and visualized using Node-RED, which will also be used to set up real-time alarms when any parameter reaches a predefined threshold indicating potential fire. A LoRaWAN gateway will serve as the communication hub, connecting the sensor devices to the cloud where the data can be monitored and analyzed

3.1. Solution Architecture

The architecture proposed for this project is organized into four layers, as illustrated in Fig. 3.1. The foundational layer is the Sensor Layer, where the IoT device, equipped with chosen sensors and development board, collects data from the surrounding environment. Above this is the Communication Layer, which consists of a LoRaWAN gateway. This gateway transmits sensor data from the IoT device to the Middleware Layer. Within the Middleware Layer, Node-RED processes the incoming data from the LoRaWAN gateway and subsequently stores it in a PostgreSQL database. Finally, the Application Layer is responsible for data visualization and alert generation. Here, the Node-RED Dashboard displays processed data and triggers alerts in response to any detected hazardous conditions.

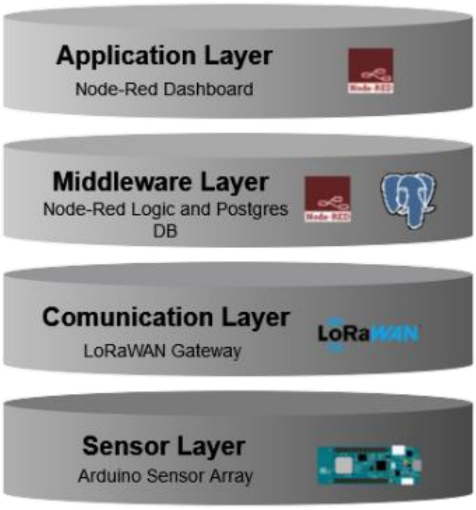

Figure 3.1 – Solution Architecture Diagram

In setting up the infrastructure for this project, Docker was employed to streamline containerized application management and ensure consistent, isolated environments. The Docker setup consists of three containers, as can be seen in Figure 3.2: one for Adminer, one for Node-RED, and one for a PostgreSQL server. Adminer is a web application tool for managing content in databases and was chosen for its simplicity and ease of use. This container-based architecture takes advantage of Docker's core strengths, such as encapsulation and portability, which simplify the deployment process and facilitate application scaling.

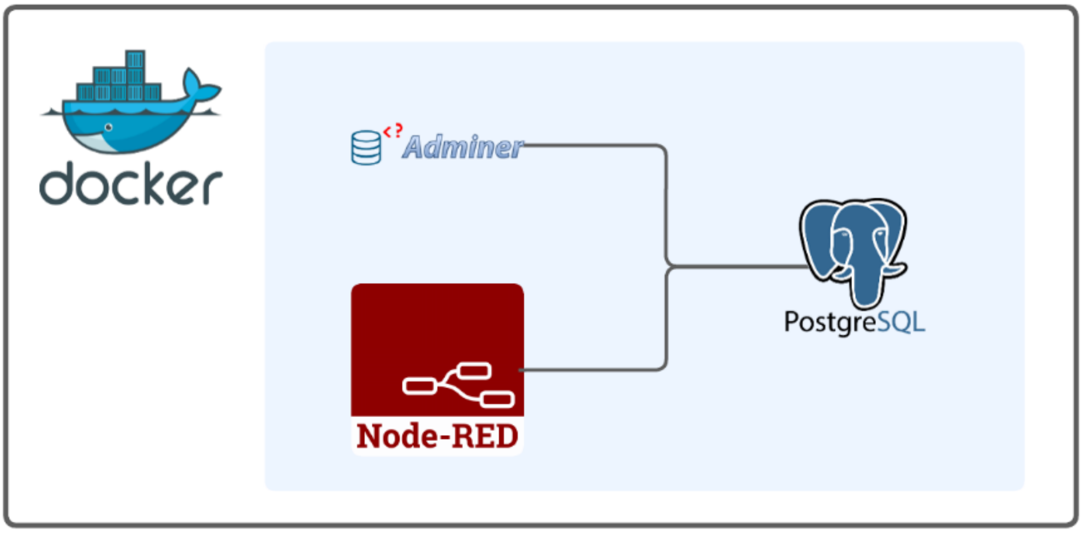

Figure 3.2 – Docker Architecture Diagram

3.2. Conceptual Mesh Network Design

To establish a mesh network of IoT devices in a forested region, the network must prioritize coverage, redundancy, and energy efficiency. The devices should be placed to ensure communication ranges while accounting for environmental obstacles such as dense foliage, uneven terrain, and varying elevation. An ideal node placement would deploy devices at intervals of 300-500 meters, although this range could be extended. Placing these devices on elevated structures such as poles or tall trees can enhance signal propagation and mitigate obstructions caused by vegetation.

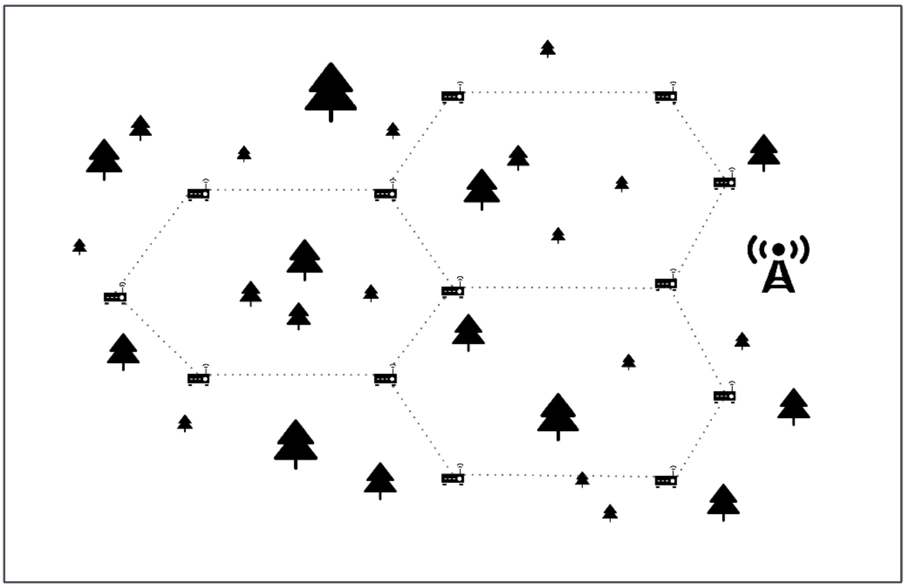

Figure 3.3 – Mesh Network in a Hexagonal Topology

The network topology should be designed for redundancy to prevent communication failures in case of a node malfunction. Hexagonal (as shown in Figure 3.3) or triangular grid layouts would ensure that each node has multiple neighbors. Lora Gateways should be placed within reachable distance of all nodes, these gateways should, ideally, be placed every 2-5 kilometers, depending on network size and the transmission range of each device.

3.3. IoT Device Design

3.3.1. Development board

Figure 3.4 – Arduino MKR1310 and 868MHz Antenna

The development board chosen for this project was the Arduino MKR WAN 1310, shown in Figure 3.4, which is a microcontroller board designed for IoT applications, particularly focusing on LoRa and LoRaWAN connectivity. It features a SAMD21 Cortex®-M0 32-bit ARM® MCU and an onboard Murata CMWX1ZZABZ LoRa® module, making it capable of long-range communication with low power consumption.

The board comes with several GPIO pins, analog and digital interfaces, an I2C interface for connecting sensors and an 868MHz antenna. The MKR WAN 1310 is suitable for applications that require remote data collection, environmental monitoring, and other IoT projects that benefit from the LoRa® protocol's range and low power characteristics.

Active Power Consumption: ~ 100mW

Sleep Power Consumption: ~0.1551mW

3.3.2. CO2, Relative Humidity and Temperature Sensor

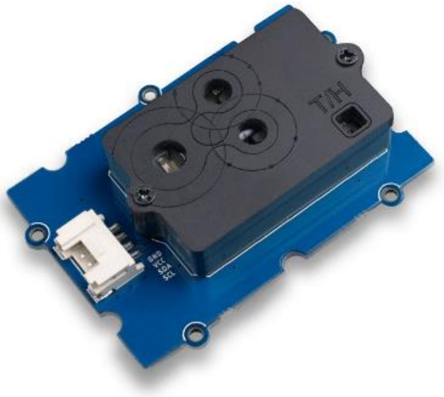

Figure 3.5 – Groove SCD30

The Grove SCD30 is a high-precision CO2 sensor module that also measures temperature and relative humidity. It is based on the Sensirion SCD30 sensor and is designed for easy integration with various microcontroller platforms, including Arduino and Raspberry Pi, using the Grove connector system. However, for this project a basic I2C connection will be used.

The SCD30 uses non-dispersive infrared (NDIR) technology to accurately measure CO2 concentrations from 0 ppm to 10,000 ppm, making it ideal for indoor air quality monitoring, HVAC systems, and other environmental sensing applications.

Active Power Consumption: ~ 375mW

3.3.3. PM2.5 Sensor

Figure 3.6 – Grove HM3301

The Grove HM3301 is a high-precision laser particulate matter (PM) sensor module, designed to measure the concentration of particulate matter in the air, specifically PM1.0, PM2.5, and PM10. It uses laser scattering technology to detect particles as small as 0.3 micrometers, providing accurate real-time data on air quality.

The HM3301 is equipped with a fan to draw in ambient air, ensuring consistent sampling, and outputs data via I2C, making it compatible with a wide range of microcontroller platforms, including Arduino and Raspberry Pi. This sensor is particularly useful for indoor air quality monitoring, pollution detection, and environmental sensing applications.

Active Power Consumption: ~ 375mW

3.3.4. CO Sensor

Figure 3.7 – Groove MQ9

The CO Senser used in this project is the Grove MQ-9, a gas sensor module designed to detect carbon monoxide (CO) and other combustible gases such as methane and LPG. It is based on the MQ-9 sensor, which uses a tin dioxide (SnO_2) semiconductor to detect gas concentrations in the air. The sensor provides an analog output, which reflects the concentration of the gases.

The MQ-9 is particularly sensitive to carbon monoxide and is commonly used in applications like gas leak detection, air quality monitoring, and safety systems.

Active Power Consumption: ~ 750mW

3.3.5. Solar power management board

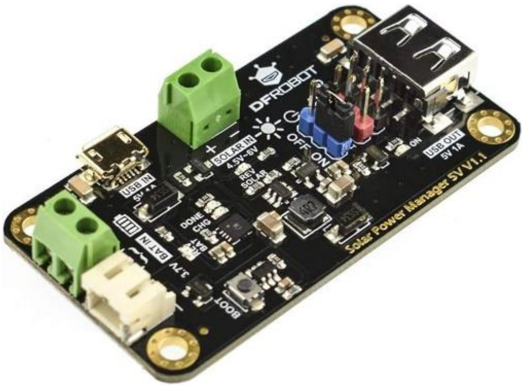

Figure 3.8 – DFRobot 5V Solar Panel Manager board

The DFRobot 5V Solar Power Manager v1.1 is a power management module designed to efficiently manage solar energy for powering small electronics projects. It can manage the input from a solar panel and regulate it to provide a stable 5V output, suitable for powering microcontrollers, sensors, and other low-power devices.

The module includes a built-in lithium battery management system, allowing it to charge a connected Li-Po using solar energy while providing protection features such as overcharge, over-discharge, and short-circuit protection. It also has multiple power outputs to support various devices and can automatically switch between solar, battery, and USB power sources depending on availability.

3.3.6. Sensor array diagram

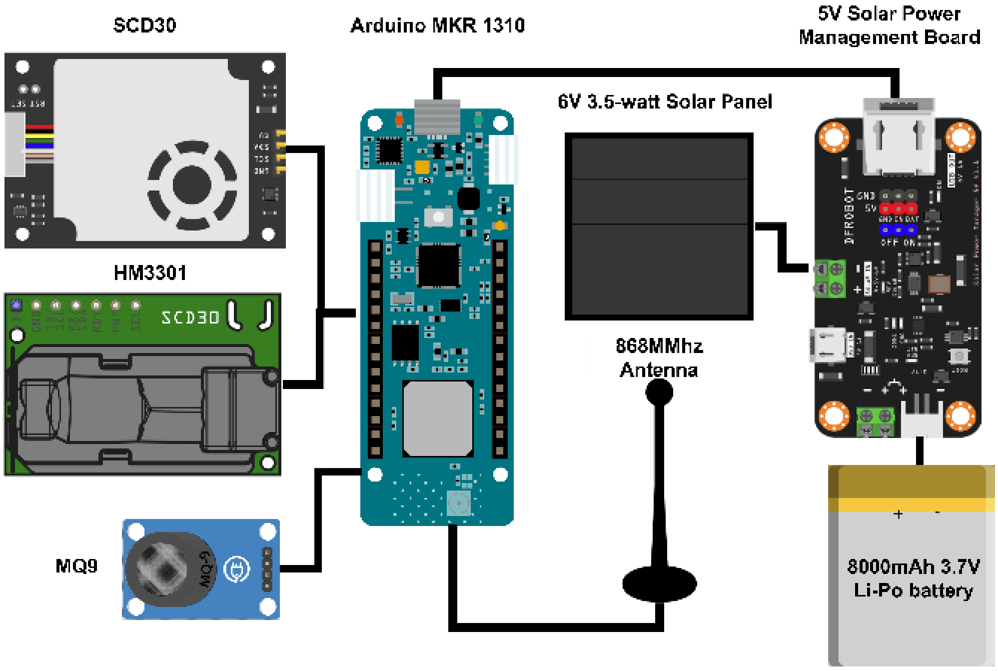

Figure 3.9 – Sensor Array Diagram

Fig. 3.9 illustrates a simplified circuit diagram of the proposed IoT device. The system is managed by an Arduino MKR1310 microcontroller, which is powered by an 8000mAh, 3.7V Li-Po battery. The battery is rechargeable via a solar-powered system consisting of a 5V solar power management unit and a 6V, 3.5-watt rated solar panel.

To optimize energy consumption, the SCD30 and HM3301 sensors are controlled by a MOSFET circuit, which is managed by the Arduino to selectively power these components on and off as needed. In contrast, the MQ-9 sensor, which has the highest energy consumption among the components, must remain continuously powered due to its 24-hour pre-heating requirement.

3.4. Power Consumption

3.4.1. Full Power Mode – Constant Reading and Transmission

In full power operation, all components of the system are actively reading, leading to a constant power draw. This mode, while acquiring real-time data and transmitting it, results in the highest possible energy consumption. For the system under consideration, which includes the Arduino MKR 1310, Grove HM3301, Grove SCD30, and Grove MQ9.

$$P_{total}=100+375+375+750=1600mW=1.6W \tag{1}$$

$$DPC=1.6W\times 24h=38.4Wh/day \tag{2}$$

$$SPI=3.5W\times 5h=17.5Wh/day \tag{3}$$

$$ED=38.4-17.5=20.9Wh/day \tag{4}$$

$$BL=\frac{29.6Wh}{20.9Wh/day}\approx 1.42\text{ days} \tag{5}$$

The total power consumption (1) of the system (Ptotal) is 1.6 watts, corresponding to a daily power consumption (DPC) of 38.4Wh (2). When powered by an 8000mAh, 3.7V Li-Po battery, which provides 29.6Wh of energy storage, the system can operate autonomously for approximately 1.42 days with a full battery life (BL). The BL duration is extended with the inclusion of a daily solar power input (SPI) of 17.5 Wh. The energy deficit (ED), representing the shortfall between energy consumption and energy supply, is also considered in the system's overall energy management (4).

3.4.2. Efficiency mode – Intermittent Readings and Transmission

To optimize energy consumption and extend battery life, the system can be configured to operate in intermittent mode. In this configuration, the Arduino MKR 1310 and selected sensors (HM3301 and SCD30) remain in a low-power sleep state for most of the time, waking only every 15 minutes to take readings and transmit data. However, the Grove MQ9 sensor, due to its requirement of a 24-hour preheating period, remains continuously active.

The duty cycle for the active components is defined as:

$$P_{total}=3.48+12.49+12.49+750=778.46mW \tag{7}$$

Thus, the daily power consumption (DPC) is:

$$DPC=0.778W\times24h=18.67Wh/day \tag{8}$$

The energy deficit (ED), representing the shortfall between energy consumption and solar power input (SPI), is calculated as:

$$ED=18.67\text{-}17.5=1.17Wh/day \tag{9}$$

The battery life (BL), assuming the same additional solar input if full power mode, can be estimated by:

$$BL=\frac{29.6Wh}{1.17Wh/day}\approx25.3 \text{ days} \tag{10}$$

On average, the system consumes 0.778 W (7), resulting in an energy deficit of 1.17Wh/day (8). Under these conditions, the battery would last approximately 25.3 days (10), making this setup viable for long-term operation in areas with moderate sunlight (approximately 5 hours of sunlight per day).

To achieve full system sustainability, the required power input (RPI) is:

$$RPI=\frac{18.67Wh/day}{5h}=3.73W \tag{11}$$

For complete self-sufficiency, a solar panel capable of providing at least 3.73 W is required. However, to account for periods of insufficient sunlight, it is advisable to use a solar panel with a higher power output. For example, a 10 W solar panel, under the same sunlight conditions, would provide 50Wh/day, resulting in a surplus of 11.6Wh/day. This excess energy would be ideal for extended periods of low sunlight, improving the system’s reliability and long-term viability as well, for a self-sustainable solution.

3.5. 3D Modeled Enclosure

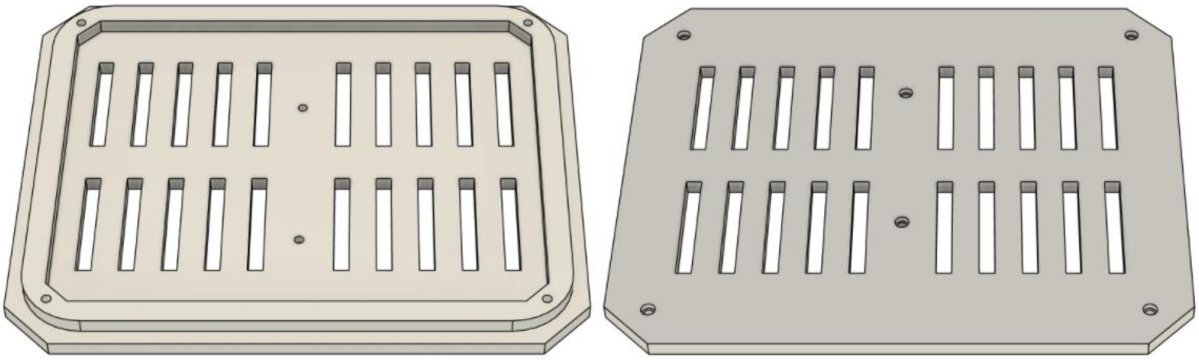

Figure 3.10 – Enclosure bottom lid model

To house the prototype solution, a four-part enclosure was designed with Fusion360. Figure 3.10 illustrates the bottom lid of the enclosure's base, which incorporates louvered air vents to allow airflow to the sensors used in this project.

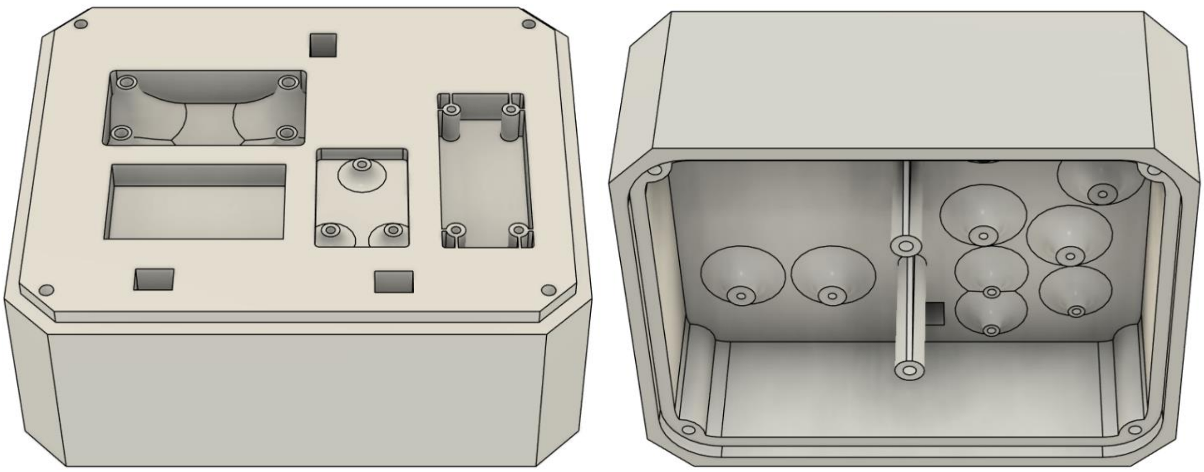

Figure 3.11 – Enclosure base model

Figure 3.11 presents the base of the model. The upper surface of the base is designed to support the core electronic components, including the Arduino MKR 1310, the DFRobot 5V solar power manager board, the 3.7V Li-Po battery, and the I2C Grove expansion board.

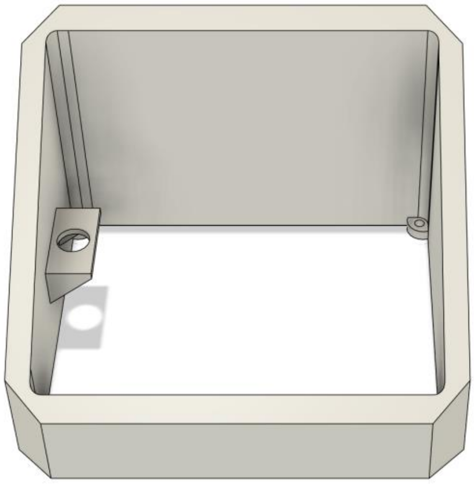

Figure 3.12 – Enclosure top model

In Figure 3.12, the top of the base is modeled with a 30º angled slant to optimize solar exposure for the attached solar panel. The base also includes a slot for a power switch, which allows to turn ON/OFF the Arduino and its sensors.

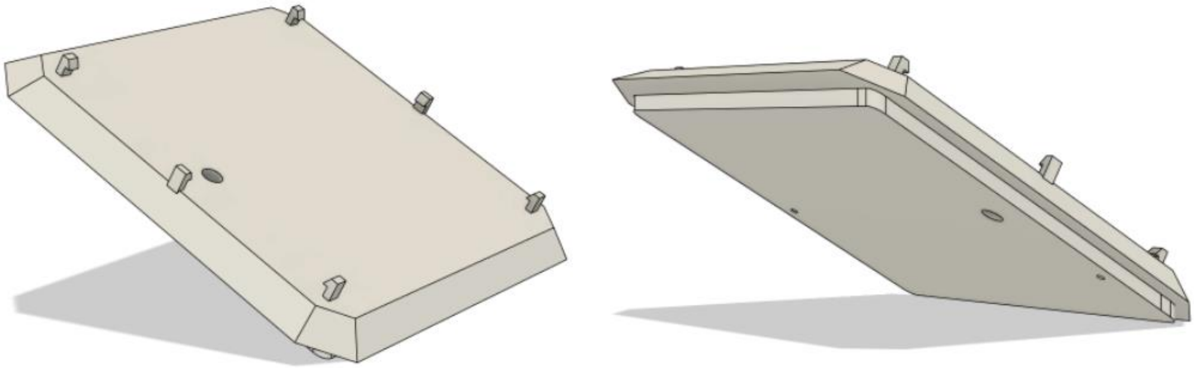

Figure 3.13 – Enclosure top lid model

Figure 3.13 shows the top lid, the final component of the enclosure. The top lid features a hole for the passage of solar panel wires and is equipped with hooks around the edges to securely hold the solar panel in place.

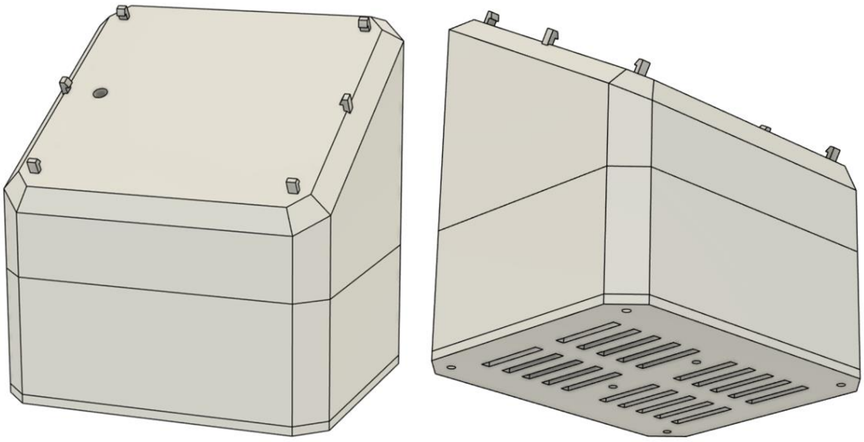

Figure 3.14 – Fully assembled enclosure model

Finally, in Figure 3.14, the full model is assembled.

3.5.1. 3D Printing and Final Prototype

To turn the modeled enclosure into a physical model to be used as the solution's enclosure, the author recurred to 3D printing. Specifically, a BambuLab P1S was used, along with Acrylonitrile Styrene Acrylate (ASA) filament, chosen for its high resistance to heat and ultraviolet (UV) light. This approach significantly sped the prototyping phase and had reduced costs compared to alternative methods such as injection molding.

However, there were several challenges associated with printing ASA due to its demanding properties, such as warping and layer adhesion issues. These issues required multiple printing iterations, remodeling of the enclosure, and additional research into 3D printing techniques to achieve a successful print. The following Figures illustrate the printed and assembled prototype solution.

Figure 3.15 shows the fully assembled prototype with the solar panel attached. The bottom view shown in figure 3.16 illustrates the vented lid so ambient air can reach the sensors.

The microcontroller, battery and solar management board are easily accessible due to the magnetic lock of the top lid, as shown in figure 3.17

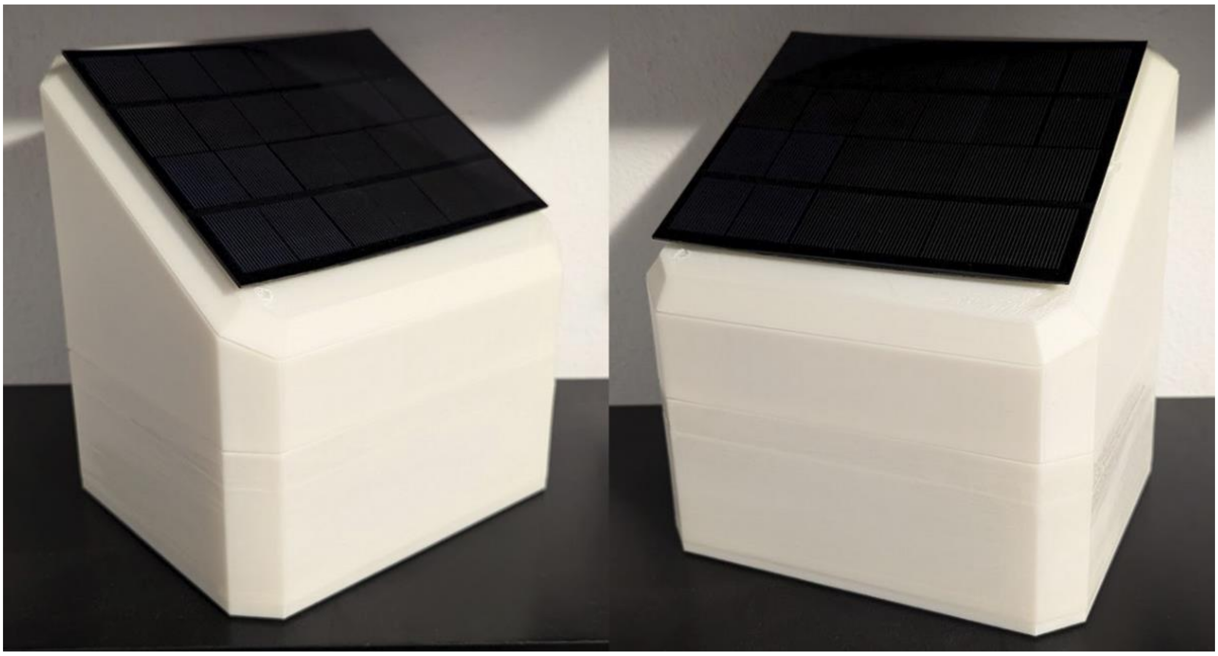

Figure 3.15 – Fully assembled 3D printed prototype

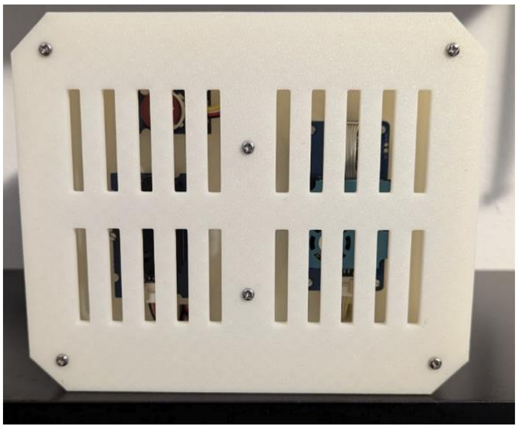

Figure 3.16 – Fully assembled prototype (bottom side)

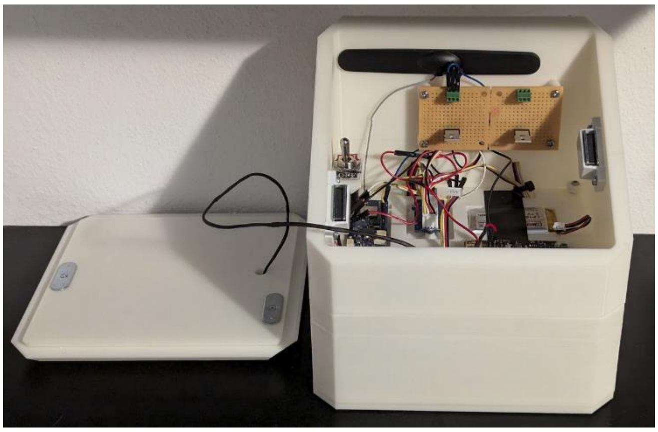

Figure 3.17 – Fully assembled prototype (electronics)

3.6. Node-RED Dashboard Design

The user interface (UI) was developed using Node-RED due to its ease of use and the variety of IoT tools available. The UI consists of three main panels: one with an interactive map, another displaying a list of registered devices, and a third panel dedicated to displaying sensor data from these devices.

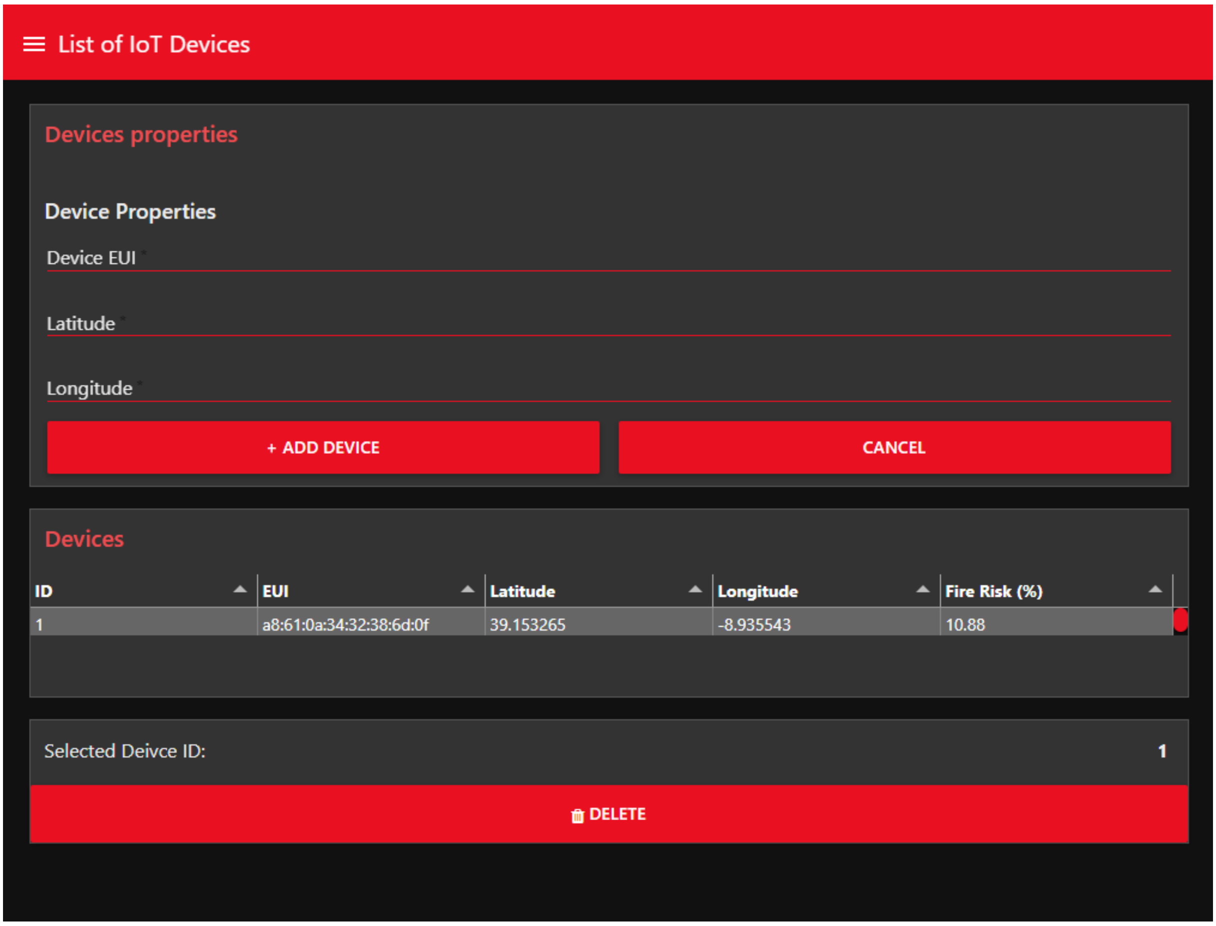

Figure 3.18 – List IoT devices – Node-Red UI

Figure 3.18 shows a screenshot of the List of IoT Devices, where users can add or remove devices. The table provides key information such as the Device EUI, location, and the fire risk probability detected by the sensors.

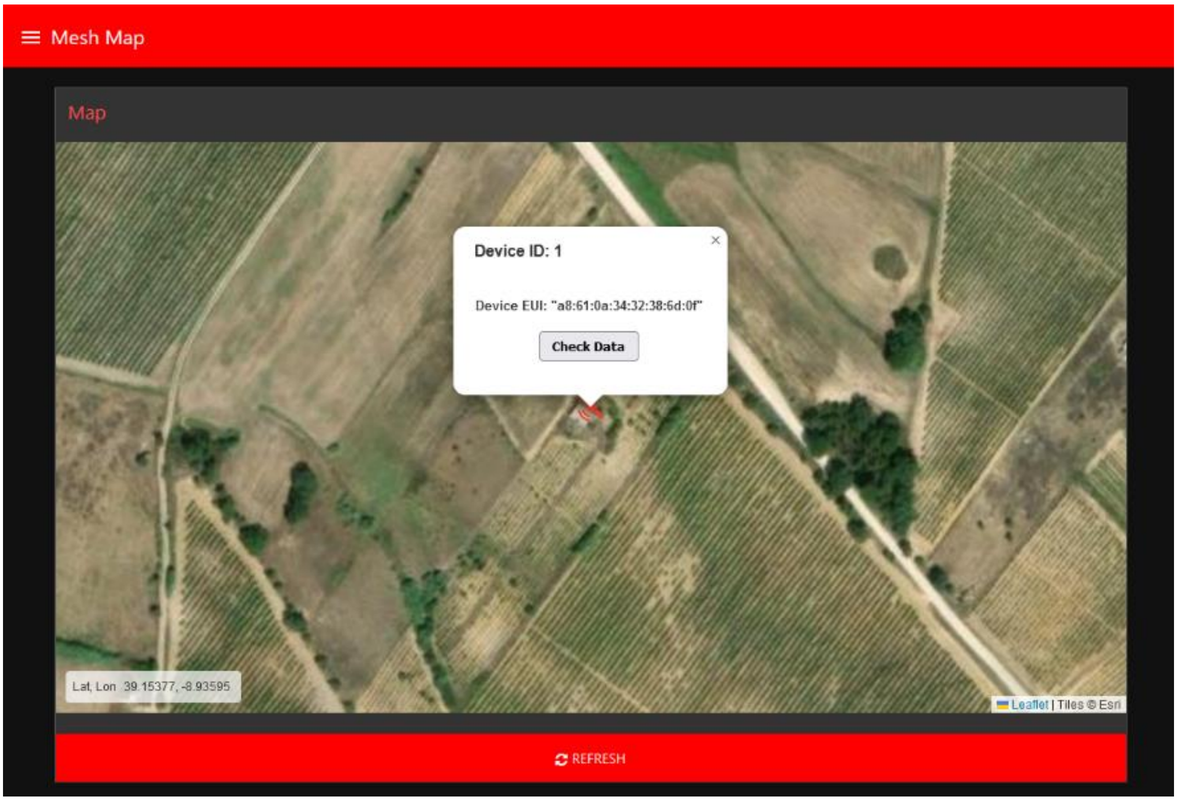

Figure 3.19 – Interactive Map with IoT devices – Node-Red UI

Fig. 3.19 presents an interactive map displaying icons with the precise locations of IoT devices. This visualization enables users to identify the exact position of each device and access the sensor data being transmitted in real-time.

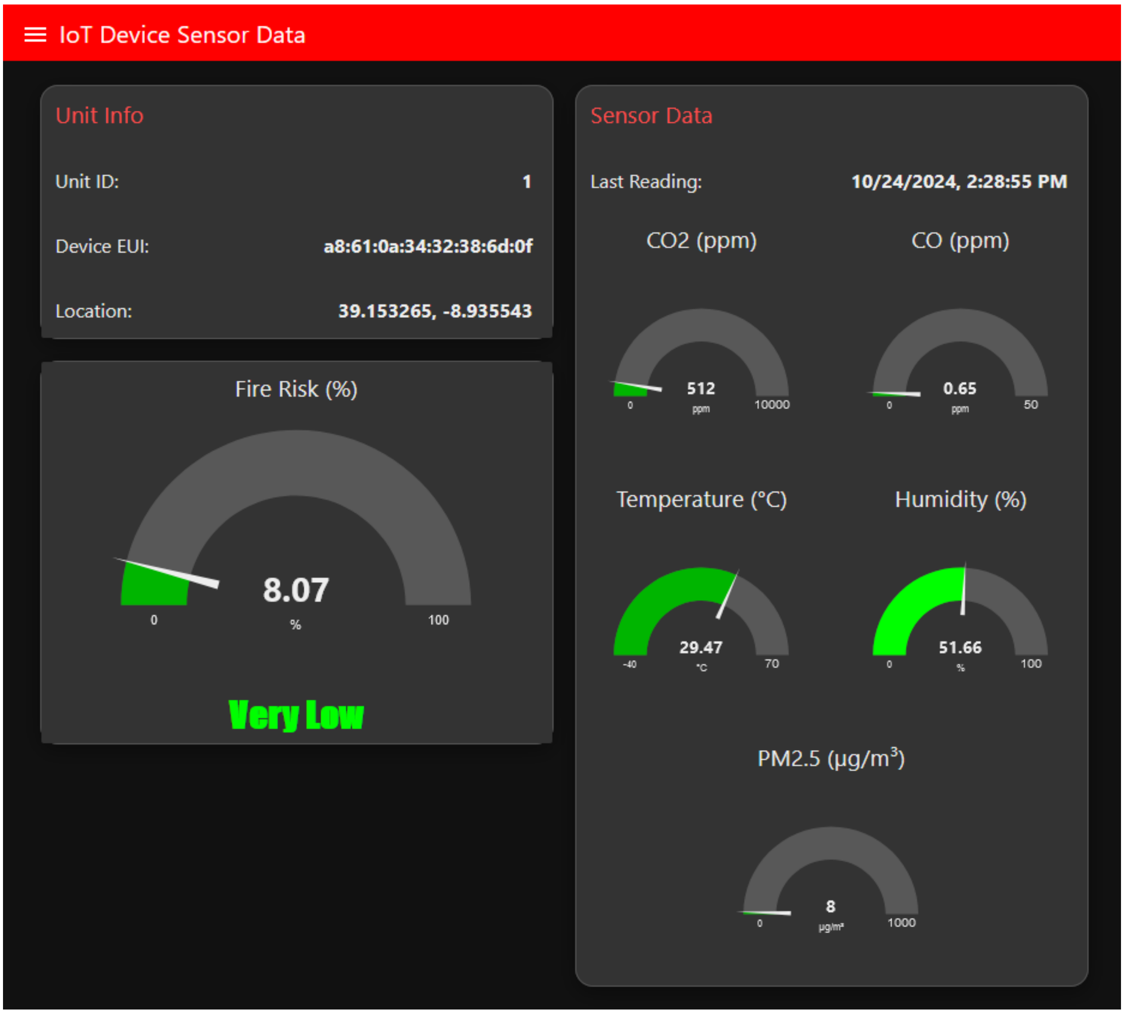

Figure 3.20 – Sensor data from IoT device – Node-Red UI

Upon selecting a device from the interactive map, the user is redirected to the IoT Device Sensor Data panel. This panel displays the latest sensor readings transmitted by the selected device, as shown in figure 3.20.

3.7. Fire Risk Calculation Method

The fire risk assessment algorithm uses sensor data to compute a risk score indicative of the likelihood of a wildfire occurrence. The system processes temperature, humidity, CO2 levels, PM2.5 concentration, and CO levels data. These parameters are normalized based on predefined thresholds. Afterwards, weighted contributions of these factors are calculated with emphasis on PM2.5 and CO levels due to their role in fire-related scenarios.

$$\text{Risk Score} = \left(wCO \times \frac{CO}{100}\right) + \left(wCO2 \times \frac{CO2}{5000}\right) + \left(wPM_{2.5} \times \frac{PM_{2.5}}{1000}\right) + \left(wTemp \times \frac{TempThreshold - Temp}{100}\right) + \left(wRH \times \frac{RHThreshold - RH}{100}\right) \quad (12)$$

The overall fire risk score is derived as a weighted sum of these normalized values to produce a risk score from 0 to 100, as shown in the equation (12). This enables a nuanced understanding of fire risk by incorporating multiple environmental factors. The resulting score hopes to provide insight for an early intervention.

CHAPTER 4

Testing

4.1. Controlled testing

Testing was conducted using a small campfire made of firewood, leaves, and semi-dried grass as fuel. The IoT device was placed 10 meters away from the fire, and data was collected over an hour under variable wind conditions. In this experiment, data was retrieved every 30 seconds.

Figure 4.1 illustrates a plot with the data taken from the CO2 sensor during an hour period. CO2 levels peaked at 600 ppm, with an average of 491.29 ppm over the testing period. Prior to igniting the fire, the CO2 level was 432 ppm, with a sharp increase of approximately 168 ppm observed within the first 10 minutes of combustion. Three additional peaks were recorded, likely corresponding to changes in wind direction.

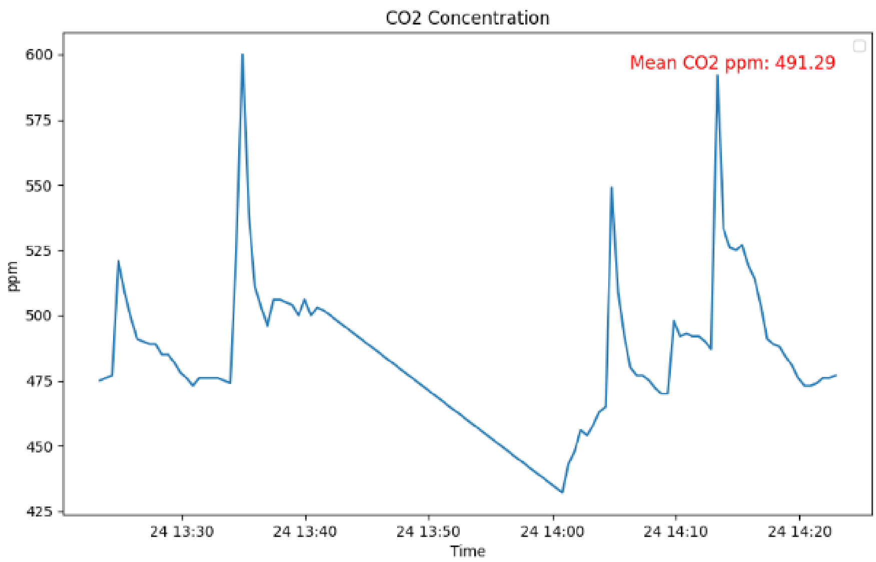

Figure 4.1 – Co2 concentration during testing

The PM2.5 concentration, which was around 8 µg/m³ before the fire, averaged 127.27 µg/m³ during combustion, with spikes exceeding 1000 µg/m³, as shown in figure 4.2. This parameter showed the greatest variation during testing.

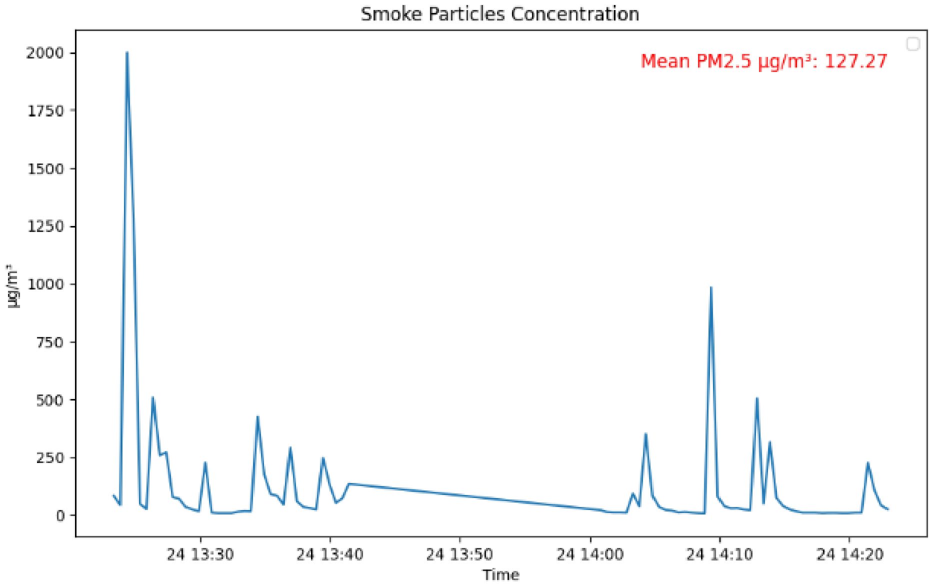

Figure 4.2 – Smoke concentration during testing

Both temperature and relative humidity (RH) experienced minor fluctuations during the test. The temperature increased by approximately 2°C, followed by a drop of 3°C, while RH oscillated by 8%.

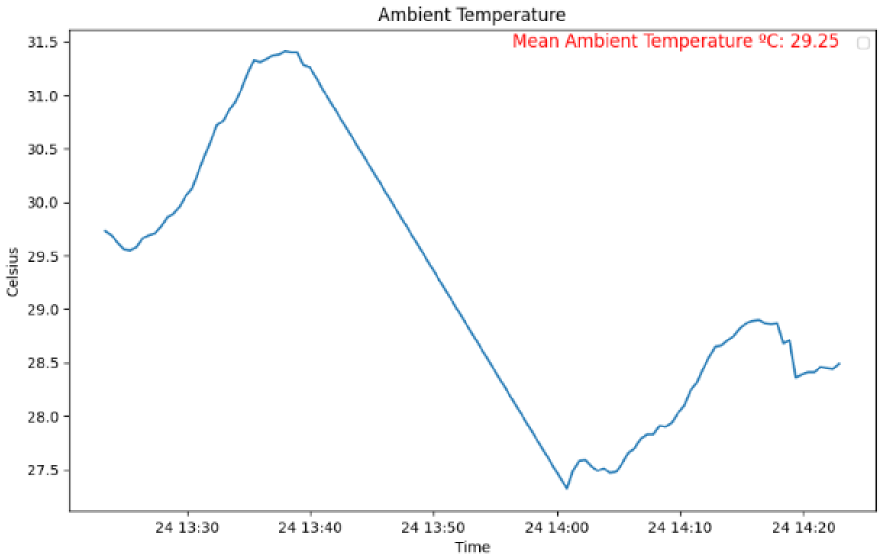

Figure 4.3 – Ambient temperature during testing

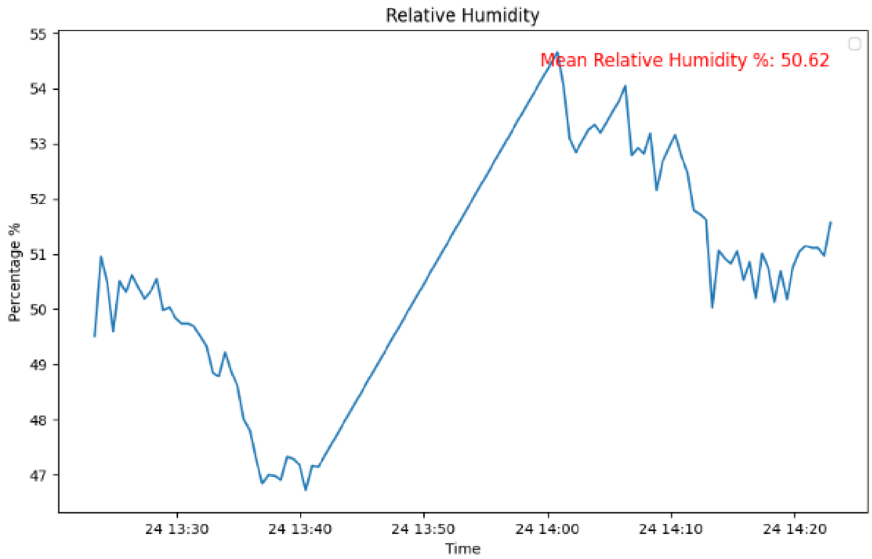

Figure 4.4 – Relative Humidity during testing

In figure 4.5, represents the values of the resistance of the MQ-9 sensor (RS) which were too high to accurately measure the corresponding ppm levels (Figure 4.6). Upon further investigation, it was discovered that the correct detection range for the chosen CO sensor is 200-1000 ppm, rather than the 10-10000 ppm claimed by some retailers. This range is too high for the sensitivity required in this project.

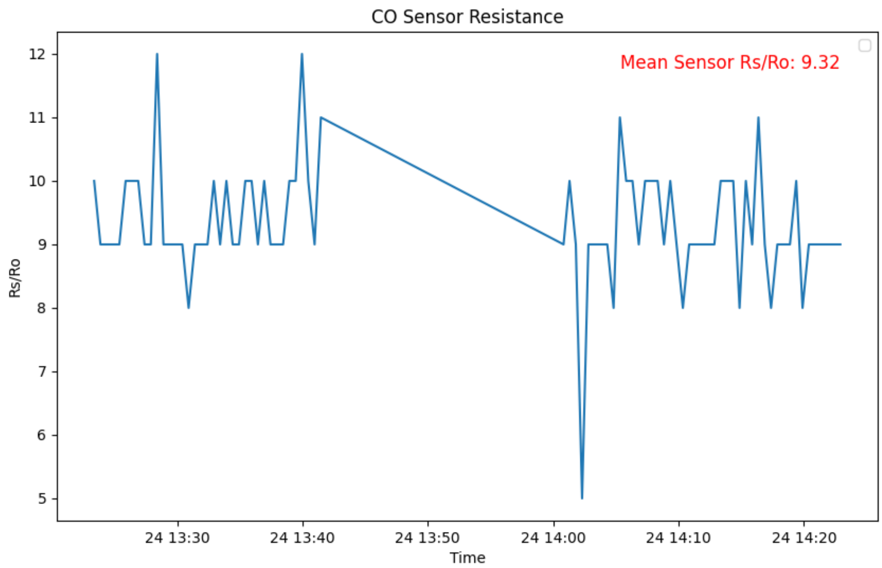

Figure 4.5 – Co concentration during testing

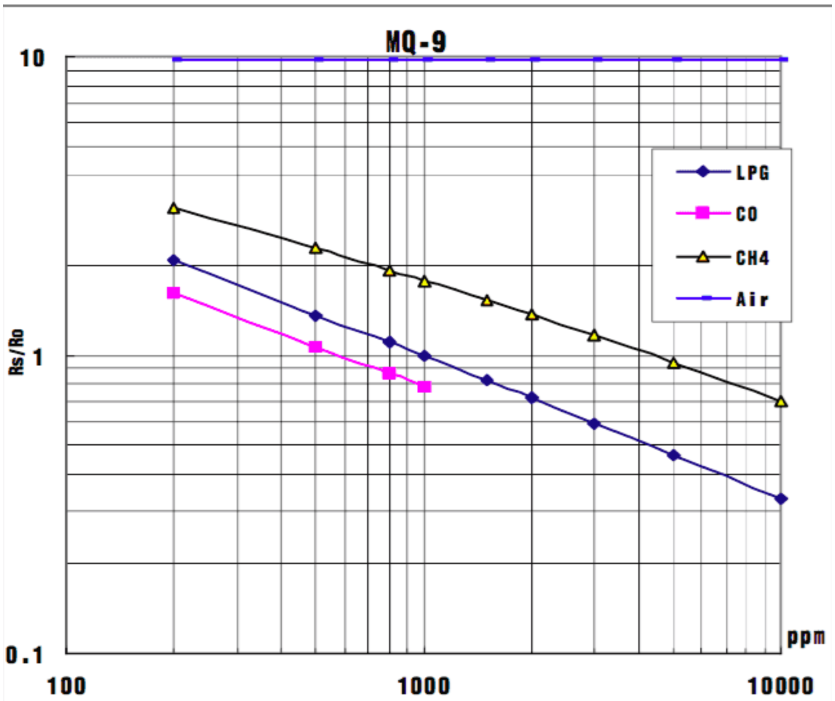

Figure 4.6 – Correlation between sensor resistance and ppm

CHAPTER 5

Conclusions and Future Work

This dissertation presented an IoT-based wildfire detection system designed to provide early warnings and real-time monitoring in remote areas. The system utilizes LoRaWAN for long-range, low-power communication, coupled with a variety of environmental sensors to detect conditions that indicate wildfire risks. The integration of solar panels for energy supply ensures that the system can operate autonomously in off-grid locations. Through initial testing, the system has shown promising results in terms of energy efficiency and data accuracy. However, further refinements are necessary to optimize its performance in real-world scenarios.

The validation of the hypotheses produced varied outcomes. Hypothesis RQ1_H1, proposing the development of a self-sustaining, low-cost IoT device, was mostly validated, though solar power optimization or a more energy efficient CO sensor remains necessary. Hypothesis RQ1_H2, concerning the triangulation of fire events using a mesh network, could not be fully achieved due to acquisition constraints. For Hypothesis RQ2_H1, the system successfully communicated with the LoRaWAN gateway, validating the use of LoRaWAN for long-range communication. Finally, Hypothesis RQ2_H2, which aimed to create a dashboard for real-time data visualization, was fully validated with an effective implementation.

Therefore, we can state that the research questions were largely addressed through this system's development and testing. While some hypotheses, such as RQ1_H2 concerning mesh triangulation, require further exploration. The remaining research questions demonstrated feasibility and functionality. This system establishes a foundation for real-world wildfire detection and monitoring, with future refinements enhancing its practical applicability.

The source code used in this code can be found at the following repository: https://github.com/DanielFreira/thesisproject.git

This work has been validated by the publication and public presentation of the article entitled "Wildfire detection based on IoT technology" in the conference "ISMSIT2024"

Limitations and Future Work

While the proposed system offers an approach to wildfire detection, certain limitations were identified that must be addressed in future iterations.

One key limitation is the need for more concrete functionality and efficiency tests in real-world scenarios. While controlled experiments have provided valuable insights, field tests are necessary to evaluate the system's reliability and performance under varying environmental factors such as signal interference, terrain, and weather conditions.

Another limitation is the current solar power setup. Although the system is designed to be energy-efficient, the solar panel used in this project does not provide sufficient energy during periods of moderate sunlight, however the use of a more efficient CO sensor might solve energy constraints at the cost of a more expensive solution. Future work must use a more powerful solar panel to make the system fully self-sustaining. Additionally, upgrading the solar power manager to a version capable of charging the battery with higher currents will ensure continuous operation, even in less ideal weather conditions.

Finally, the system currently uses the Groove MQ9 CO sensor, which requires a 24-hour stabilization period before it can provide reliable data. This long pre-heating time challenges the system efficiency. There is another limitation with its concentration detection range making it insufficient for this project. Future work will involve identifying a more efficient CO sensor capable of detecting lower concentration ranges that not only consumes less energy but also has a shorter stabilization time.

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