

PIIRRIGATE: A SMART IRRIGATION SYSTEM

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REZUMAT

Această lucrare descrie proiectarea și realizarea sistemului “Pilrrigate”. Acest sistem are ca scop eficientizarea consumului de apă și optimizarea culturilor agricole sau a grădinilor, prin utilizarea tehnologiilor moderne IoT și a comunicațiilor radio de tip LoRa. Pe măsură ce efectele încălzirii globale se fac din ce în ce mai resimțite, automatizarea și monitorizarea irigațiilor devine o necesitate. Proiectul vizează dezvoltarea unui sistem de monitorizare și control destinat fermierilor care doresc monitorizarea unor suprafețe mari de teren, dar acest sistem poate fi folosit și pentru sere inteligente sau grădinărit normal.

Proiectul utilizează o arhitectură bazată pe microcontrolere Raspberry Pi și T-Beam LILYGO ESP32 LoRa. Aceste componente sunt folosite pentru colectarea și transmiterea datelor în timp real. Sistemul permite monitorizarea parametrilor esențiali (umiditate, temperatură, umiditatea solului și cantitatea de ploaie) prin senzori care sunt conectați la nodurile ESP32. Dupa colectare, datele urmează să fie transmise către un gateway care comunică apoi cu un API web dezvoltat în .NET. Apoi datele urmează să fie stocate într-o baza de date PostgreSQL și trimise folosind SignalR către o aplicație web pentru a fi vizualizate în timp real de către utilizatori.

Utilizatorii au la dispoziție o interfață web care le permite atât vizualizarea datelor în timp real cât și vizualizarea datelor istorice și controlul manual al sistemului. De asemenea, acest sistem implementează un mecanism de înregistrare dinamică a nodurilor în rețea, lucru care permite extinderea facilă a sistemului.

Prin integrarea componentelor hardware și software într-o soluție coerentă, Pilrrigate demonstrează fezabilitatea și eficiența unui sistem IoT dedicat agriculturii inteligente, cu un impact potențial în reducerea consumului de apă și creșterea randamentului agricol.

ABSTRACT

This paper describes the design and implementation of the “Pilrrigate” system. The purpose of this system is to optimize water consumption and improve the management of agricultural crops or gardens by using modern IoT technologies and LoRa radio communications. As the effects of global warming become increasingly evident, the automation and monitoring of irrigation systems is becoming a necessity. The project aims to develop a monitoring and control system intended for farmers who need to oversee large areas of land, but it can also be used for smart greenhouses or regular gardening.

The project uses an architecture based on Raspberry Pi microcontrollers and T-Beam LILYGO ESP32 LoRa modules. These components are used for the real-time collection and transmission of data. The system enables the monitoring of essential parameters (humidity, temperature, soil moisture, and rainfall) through sensors connected to ESP32 nodes. After collection, the data is transmitted to a gateway, which then communicates with a web API developed in .NET. The data is stored in a PostgreSQL database and sent in real time via SignalR to a web application, where it can be viewed by users. Users have access to a web interface that allows them to visualize both real-time and historical data, as well as to manually control the system. Additionally, the system implements a dynamic node registration mechanism, enabling easy expansion of the network. By integrating both hardware and software components into a coherent solution, Pilrrigate demonstrates the feasibility and efficiency of an IoT-based system dedicated to smart agriculture, with the potential to reduce water consumption and increase agricultural productivity.

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1. INTRODUCTION

1.1 CONTEXT

Agriculture is a vital sector that plays a crucial role in sustaining human life and the economy. Agriculture automation and optimization has become a major concern in recent years. As the global population continues to grow, the demand for food is increasing and the developing need for food along with the effect of climate changes are forcing the agricultural industry to adapt and innovate[1].

In the last 35 years, the world has seen a doubling of the agricultural production. This has been achieved through the use of different fertilizers, pesticides and herbicides. This doubling was associated with a 6.87-fold increase in nitrogen fertilization, a 3.48-fold increase in phosphorus fertilization and 1.68-fold increase in the amount of irrigated cropland [2]. In addition, the water consumption is expected to increase by 50% by 2050 [3].

This project aims to address the challenges of water scarcity and the need of efficient irrigation systems by presenting the plan, the implementation, the results and future work of a system that can be used in different scenarios and is meant to help reducing the water consumption and increasing the agricultural productivity. The Pilrrigate project intends achieve this by developing an innovative irrigation system that leverages the power of IoT and LoRa radio communication technologies. The main focus of this project is to create a system that can be easily used in different agricultural settings, starting from small gardens to large farms and even smart greenhouses. Beside this, I wanted to create a system that is easy to use and can be extended with ease.

The ESP32 boards with sensors are responsible for collecting the data. Then data is sent using LoRa to another ESP32 board that acts as a gateway connected to a Raspberry Pi, which is responsible for sending the data to a web API. The web API is developed in .NET and is responsible for storing the data in a PostgreSQL database. The data is then sent to a web application using SignalR, which allows real-time communication between the server and the client. The web application is responsible for displaying the live data and the historical data and also for providing a way to control the system manually and to add new nodes to the system.

This system takes advantage of the LoRa radio communication technology, which allows for long-range communication with low power consumption. Meaning that the system can be used in remote areas and it will work even if the internet connection is not available to all the nodes. The Raspberry Pi is the only component of this system that needs to be connected to the internet. Other components can be scattered on an area of 10km or more, depending on the environment and the node setup (mesh or star topology).

1.2 MOTIVATION

The reason why I choose to create such a system was fueled by my passion for technology and smart agriculture. Besides this, I like to observe the data path, from the moment it is collected by the sensors, to the moment it is displayed in a web application. I have always been interested in pieces of technology that can be used to solve real world problems and now I had the chance to create such a system. Initially, I wanted to create a smaller system for my own garden, but then I realized that this system can be used in a larger scale and can be adapted to different scenarios.

This project is also motivated by the opportunity to apply core concepts of computer science, such as API design, data management, distributed systems and IoT to build a cost-effective and scalable smart irrigation system. This project intends to provide not only a system for irrigation, but also a platform that can be used in different scenarios, such as smart greenhouses, meteorological stations, or even smart cities.

1.3 OBJECTIVES

The main objective of this project is to develop a system that leverages IoT, cloud services, and modern software development principles to optimize irrigation processes and reduce the water usage in agriculture. The focus of this project is to provide a theoretical approach of the system, but also to present the implementation details and the results of the system. At the end of this project the result should comprise the system architecture, including the hardware and software components, and the implementation details of the system. The implementation details will include the hardware and software components used, the communication protocols used, the data management and storage, and the user-interface design. To be more specific, the objectives of this project are:

- Develop a cost-effective and scalable smart irrigation system that can be used in different agricultural settings.
- Leverage IoT and LoRa radio communication technologies to create a system that can operate in remote areas with low power consumption.
- Provide a user-friendly web application for real-time monitoring and control of the irrigation system.
- Implement a modular architecture that allows for easy extension and customization of the system.
- Ensure data security and privacy by implementing best practices in API design and data management.

1.4 SCOPE AND LIMITATIONS

Scope of this project includes the design, implementation, and evaluation of a smart irrigation system. The system will be designed to collect data from environmental sensors,

such as soil moisture, temperature, and humidity, process this data through a web API, and provide a user friendly web application for real-time monitoring and control.

Key features of the system include:

- Data collection from environmental sensors using LILYGO Meshtastic AXP2101 T-Beam V1.2 ESP32 LoRa boards.
- Long-range communication using LoRa radio technology.
- Data processing and storage using a web API and PostgreSQL database.
- Real-time monitoring and control through a web application.
- Modular architecture for easy extension and customization.

Despite the comprehensive scope of this project, there are some limitations that need to be considered:

- Hardware limitations: The system is designed to work with specific components, any changes to the hardware may require significant changes in the project.
- This specific system will be tested in a controlled environment, so the result may not be representative of real-world scenarios.
- Reliability and calibration of the hardware components are assumed to be optimal, but they are not guaranteed.
- Weather prediction and other external factors are outside the scope of this project, the system will not take into account weather forecasts.
- Energy consumption and power management analysis are not included in the scope of this project.
- The UI design is focused on functionality and usability, but it may not be visually appealing or optimized for all devices.
- Machine learning and advanced data analytics are not included in the scope of this project.

1.5 METHODOLOGY OVERVIEW

The methodology adopted for this project is structured around the typical software development lifecycle, beginning with the requirements gathering and analysis, followed by the design, implementation, testing, and evaluation phases. This approach ensures that the system is developed in a systematic and organized manner, allowing for the creation of a robust and reliable smart irrigation system.

System requirements were gathered based on a research of modern irrigation practices, with a great focus on water consumption usage and the need for real-time monitoring and control. These requirements helped identifying core functionalities of the

system, such as data collection from environmental sensors, processing, storage, and user interface design. Non-functional requirements, such as reliability and scalability were also taken into account during the requirements gathering phase.

The system architecture was designed using a layered approach. The hardware layer includes the sensors, the ESP32 boards and the Raspberry Pi. It is responsible for environmental data collection. The communication layer includes all protocols and technologies used for data transmission, such as LoRa, MQTT and HTTP. The data processing layer includes the IoT Hub, the webApi and the PostgreSQL database. Finally the user interface layer includes the web application that provides real-time monitoring and control of the system.

2. STATE OF THE ART

2.1 INTRODUCTION

The state of the art chapter provides an overview of the current state of smart irrigation systems and their applications in agriculture. This chapter will explore the existing technologies, methods, and solutions used in smart irrigation. It will also highlight the gaps and challenges in the current systems, and how the Pilrrigate project aims to address these issues.

2.2 EXISTING SMART IRRIGATION SOLUTIONS

2.2.1 TYPES OF SMART IRRIGATION SYSTEMS

There are several types of smart irrigation systems used in modern agriculture:

- **Weather-Based Controllers**

These system take advantage of available weather data, such as temperature, humidity, and rainfall forecasts, to optimize irrigation schedules. This is not the most precise method as it does not use data from the soil, but it represent a good alternative for large areas.

- **Soil Moisture-Based Controllers**

Soil moisture based controllers use sensors that are placed in the soil to measure the moisture level and adjust the irrigation accordingly. These are more precise than weather-based controllers, as they take into account the actual moisture level in the soil, but they require more maintenance and calibraiton [4].

- **Hybrid Systems**

Many modern systems utilize a hybrid approach, combining data from both weather feeds and soil moisture sensors for more accurate and resilient irrigation decisions. Some research also explores "hybrid" in terms of integrating different energy sources (e.g., solar and wind) to power the systems or combining various irrigation methods (like drip and sprinkler) under one smart control[5].

The Pilrrigate project place itself in the category of hybrid systems, using both soil moisture sensors and weather sensors to collect data.

Some of the most popular hybrid smart irrigation systems include:

- **Netafim's Precision Irrigation System**

This system cobines data from soil moisture and flow sensors with sattelite weather data and predictive analytics to optimize the irrigation proccess.

Key features include:

- * Real-time monitoring of soil moisture levels and weather forecasts.

- * Automated irrigation scheduling based on weather forecasts.
- * AI-based algorithms to optimize the irrigation timing and duration.

– **CropX Smart Farming System**

CropX is a cloud based platform that integrates soil moisture sensors, weather data and machine learning algorithms to optimize the irrigation process.

Key features include:

- * Irrigation recommendations based on soil variability, crop type and weather.
- * Farmers can apply recommendations or integrate with automated irrigation controllers.
- * Easy to scale and adapt to different farm sizes from small to large-scale farms.

– **Toro EVOLUTION® Series Controller with Smart ET Sensor**

Combines basic sprinkler system hardware with smart sensors and connectivity, offering both manual and intelligent irrigation options. The evaporation sensors are used to measure the amount of water lost through evaporation and adjust the irrigation accordingly.

Key features include:

- * Can be programmed manually or connected to a local weather station.
- * Smart ET sensor measures evaporation rates and adjusts irrigation schedules.
- * Compatible with smart devices for remote monitoring

2.3 COMPARATIVE ANALYSIS OF SMART IRRIGATION SYSTEMS

The table below provides a comparative analysis of some of the most popular smart irrigation systems available today and the Pilrrigate system.

Feature	Netafim	CropX	Toro ET	Pilrrigate
Irrigation Type	Drip	Any	Sprinkler	Custom
Automation	High (AI)	Med-High	Medium	Medium
Sensors	Soil, flow, weather	Soil, temp	ET sensor	Soil, temp, rain
Weather Data	Yes	Yes	Yes	Optional
Manual Control	App/cloud	App/web	Panel/app	Web UI
AI/Analytics	Yes	Yes	No	No
Scalability	Large farms	Small-large	Residential	Small farms/gardens
Cloud Sync	Yes	Yes	Optional	Yes
Use Case	Precision agri	Smart farming	Lawn care	Small to large scale
Cost	High	Med-High	Low-Mid	Low

Table 2.1: Comparison of Smart Irrigation Systems

2.4 IOT AND LORA IN AGRICULTURE

Agriculture is one of the biggest industries, critical to the global economy and food security. With the increasing food demand, the need for efficient and sustainable agricultural has grown in the last years. The IoT (Internet of Things) is a key technology that can help to address these challenges by providing real-time data and insights into the agricultural processes. LoRa (Long Range) is a wireless communication technology that is well suited for agriculture applications. It has been invented in 2009-2010 by the company Cycleo, which was later acquired by Semtech in 2012 and until 2020 it was implemented in more than 100 million devices worldwide [6].

One approach to integrate IoT and LoRa in agriculture is to use a layered architecture. This architecture consists of four layers: data acquisition, gateways, network and application. where the sensors and actuators are connected to a LoRa gateway, which is then connected to a cloud platform. This architecture is proposed in this paper [7] and it is a similar approach to the one used in the Pilrrigate project. The sensors collect data from the environment, such as soil moisture, temperature, and humidity, and send it to the LoRa gateway using LoRa radio communication. The gateway then sends the data to a cloud platform, where it can be processed and analyzed. The cloud platform can also send commands to the actuators, such as irrigation valves, to control the irrigation process based on the data collected by the sensors.

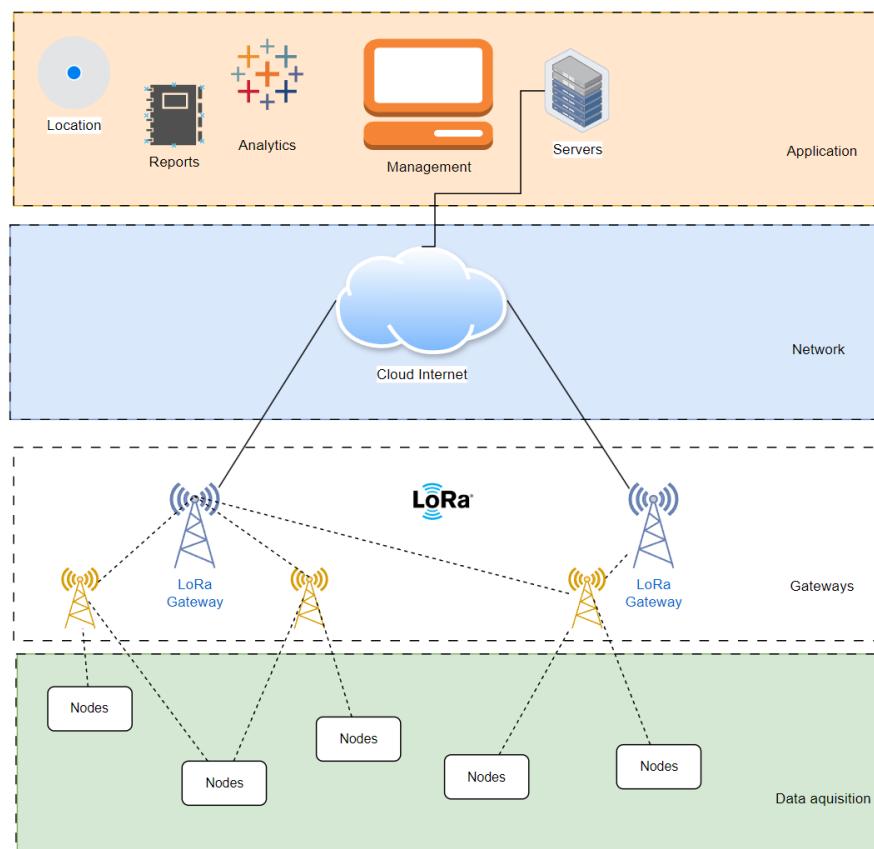


Figure 2.1: LoRa-based IoT Architecture for Agriculture

2.5 LORA VS OTHER WIRELESS TECHNOLOGIES

At this moment, there are several wireless technologies available for IoT applications. After a comparative analysis of the most popular wireless technologies used in IoT, LoRa came out as one of the most suitable technologies for smart irrigation systems because of its long range, low power consumption and scalability. The table below compares LoRa with other wireless technologies commonly used in IoT applications, such as Wi-Fi, Bluetooth (BLE), Zigbee, and NB-IoT. In this section we will analyze the capabilities of these technologies and their suitability for smart irrigation systems. The comparison is based on several features, including range, data rate, power consumption, topology, license band, scalability, cloud integration, infrastructure cost and latency.

Wifi, Bluetooth and Zigbee have a decent data rate, and very good latency, but they have a very short range and high power consumption. This makes them more suitable for local applications, such as home automation or local sensor networks. NB-IoT(Narrowband IoT) represents a potential solution for smart irrigation systems, but it has a higher infrastructure cost and requires a cellular network, which may not be available in all areas.

Feature	LoRa	Wi-Fi	Bluetooth (BLE)	Zigbee	NB-IoT
Range	2–15 km	~100 m	10–100 m	10–100 m	10–35 km
Data Rate	0.3–50 kbps	Up to 600 Mbps	Up to 2 Mbps	20–250 kbps	Up to 250 kbps
Power Consumption	Very Low	High	Very Low	Low	Low
Topology	Star (LoRaWAN)	Star	Star	Mesh	Star (cellular)
License Band	Unlicensed (ISM)	Unlicensed (2.4 GHz)	Unlicensed (2.4 GHz)	Unlicensed (2.4 GHz)	Licensed
Scalability	High	Low	Low–Medium	Medium	High
Cloud Integration	Easy via LoRaWAN	Native IP stack	Requires gateway	Requires gateway	Native via operator
Infrastructure Cost	Low	Medium	Low	Medium	High
Latency	High (seconds)	Low (ms)	Very Low (ms)	Low (ms)	Moderate
Ideal Use Case	Smart City Infrastructure	Local, high-speed data transfer	Short-range sensors/wearables	Indoor sensor networks	National-scale deployment

Table 2.2: Comparison of Wireless Technologies for Smart Irrigation

2.6 IDENTIFIED GAPS AND CHALLENGES

Despite the advancements in smart irrigation systems, several gaps and challenges remain:

- **High Costs**

Many existing systems are expensive, making them inaccessible for small farmers or home gardeners.

- **Complexity of Use**

Some systems require specialized knowledge to set up and maintain, which can be a barrier for adoption.

- **Limited Customization**

Many commercial solutions are designed for specific crops and environments and that limits their applicability to diverse agricultural settings.

- **Data Integration Issues**

Integration of data from different sources (e.g. weather, soil) can be more complex and it can lead to inefficiencies in the irrigation management.

In addition to the gaps mentioned, there are a few other issues that must be resolved, like the need for systems that can function in challenging environmental conditions, the need for dependable internet connectivity in remote locations, and data security and privacy issues.

The effect that smart irrigation systems have on the environment is another factor that must be taken into account. Even though these systems are made to use water as efficiently as possible, the manufacturing and disposal of electronic components can harm the environment. Therefore, developing sustainable and ecologically friendly systems is another challenge. This means that the systems should be built to last a long time and be simple to use, and that the parts used in them should be composed of recyclable materials.

2.7 SUMMARY

In summary, the state of the art in smart irrigation systems shows significant advancements in technology and methods, but also highlights several gaps and challenges that need to be addressed. The Pilrrigate project aims to fill these gaps by providing a cost-effective, easy-to-use, and customizable solution that leverages the power of IoT and LoRa

3. SYSTEM ARCHITECTURE

3.1 OVERVIEW

The Internet of Things (IoT) is a new technology that allows devices to connect remotely to achieve smart farming [8]. The IoT has a wide range of applications in agriculture, and it has began to influence many other industries as well, such as healthcare, transportation, and manufacturing. This was done to improve the efficiency and productivity of these industries, as well as to reduce costs and improve the quality of products and services[9].

The Pilrrigate smart irrigation system is build using a combination of hardware and software technologies. It leverages both low-power edge devices and cloud-based infrastructure to provide real-time monitoring and data collection, as well as remote control capabilities. The core components and their roles in the system are as follows:

- **ESP32 (LILYGO Meshtastic AXP2101 T-Beam V1.2 ESP32 LoRa)**

The LILYGO Meshtastic AXP2101 T-Beam V1.2 ESP32 LoRa is a development board based on the ESP32 microcontroller, it is equipped with LoRa radio communication capabilities, Wifi, Bluetooth, GPS, and a battery management system. It is used to collect data from sensors and send it to the gateway using LoRa radio communication.

- **Raspberry Pi**

Raspberry Pi is a small, affordable computer that can be used for a wide range of applications. The Raspberry Pi is the core of the Pilrrigate irrigation module, it is responsible for receiving data from the ESP32 nodes and sending it to Azure IoT Hub.

- **Azure IoT Hub**

Azure IoT Hub is a cloud-based service that enables secure and reliable communication between IoT devices and the cloud. It manages the bidirectional communication between the Raspberry Pi and the web API.

- **Web API**

The web API is developed in .NET and is responsible for receiving data from the Raspberry Pi, storing it in a PostgreSQL database, and providing a way to access the data. SignalR is used to provide real-time communication between the server and the client. It also provides a way to control the system manually and to add new nodes to the system.

- **PostgreSQL Database**

PostgreSQL is a powerful, open-source relational database management system. It is used to store the data collected from the sensors and the schedules sent to the system. It also stores the user data and the configuration of the system. The database is hosted in Neon.

- **Web Application**

The web application is developed using Angular and is responsible for displaying live, historical data and provide the user interface for controlling the system.

In the following sections, we will explore each of these components in more detail, starting with the hardware components and then moving on to the software components.

3.2 HARDWARE COMPONENTS

3.2.1 SENSORS

The Pilrrigate system uses a variety of sensors to collect data from the environment. The sensors used in the Pilrrigate system are:

- **Soil Moisture Sensor**

The soil moisture sensor is used to measure the moisture level in the soil. It is used to determine when to irrigate the plants.

- **Temperature and Humidity Sensor**

The temperature and humidity sensor is used to measure the temperature and humidity of the environment. It is used to determine the optimal conditions for plant growth and to adjust the irrigation schedule accordingly.

- **Rain Sensor**

The rain sensor is used to detect rain and prevent irrigation during rainy weather. It helps to conserve water and prevent over-irrigation.

- **Water Flow Sensor**

The water flow sensor is used to measure the flow rate of water in the irrigation system. It is used to monitor the water consumption.

- **Water Temperature Sensor**

The water temperature sensor is used to measure the temperature of the water in the irrigation system. It is used to ensure that the water temperature is within the optimal range for plant growth.

3.2.2 ESP32 (LILYGO T-BEAM)

The T-Beam ESP32 LoRa Wireless Module is a compact development board that combines an ESP32 microcontroller, LoRa transceiver (SX1278), GPS module, and a battery management system into a single unit. This board is ideal for long-range, low-power IoT applications such as mesh networks, asset tracking, smart agriculture and environmental monitoring. Besides this, it has a built-in OLED display. The communication range of the LoRa transceiver can reach up to 10 km in open areas.



Figure 3.1: ESP32 (LilyGo T-Beam) module used in Pilrrigate

3.2.3 RASPBERRY PI 4 MODEL B

The Raspberry Pi 4 Model B is a small, affordable computer that can be used for a wide range of applications. It is equipped with a quad-core ARM Cortex-A72 processor, up to 8GB of RAM, and supports dual-band Wi-Fi and Bluetooth. The Raspberry Pi 4 Model B together with an ESP32LoRa is used in the Pilrrigate project as the gateway that receives data from the ESP32 nodes and sends it to IoT Hub.

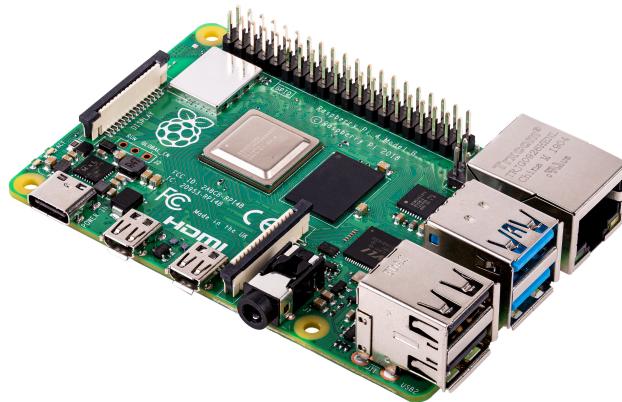


Figure 3.2: Raspberry Pi 4 Model B used in Pilrrigate

3.3 HARDWARE ARCHITECTURE

The hardware architecture of the Pilrrigate system consists of multiple ESP32 nodes that collect data from the sensors and send it to a gateway ESP32 connected to a Raspberry Pi. The Raspberry Pi acts as a gateway that receives data from the ESP32 nodes and sends it to Azure IoT Hub using MQTT protocol. The ESP32 nodes are connected to various sensors that collect data from the environment.

The ESP32 nodes are connected to the sensors and actuators as follows:

- Soil moisture (YL-69) sensor is connected to GPIO32.
- Temperature and humidity sensor (DHT11) is connected to GPIO27.
- Rain sensor (YL-83) is connected to GPIO32.
- Water flow sensor YF-S201 is connected to GPIO35.
- Water temperature sensor (DS18B20) is connected to GPIO26.
- The relay module that controls the electronic valve is connected to GPIO22.

In the figure below, you can see a simplified diagram of the ESP32 pinout and connections.

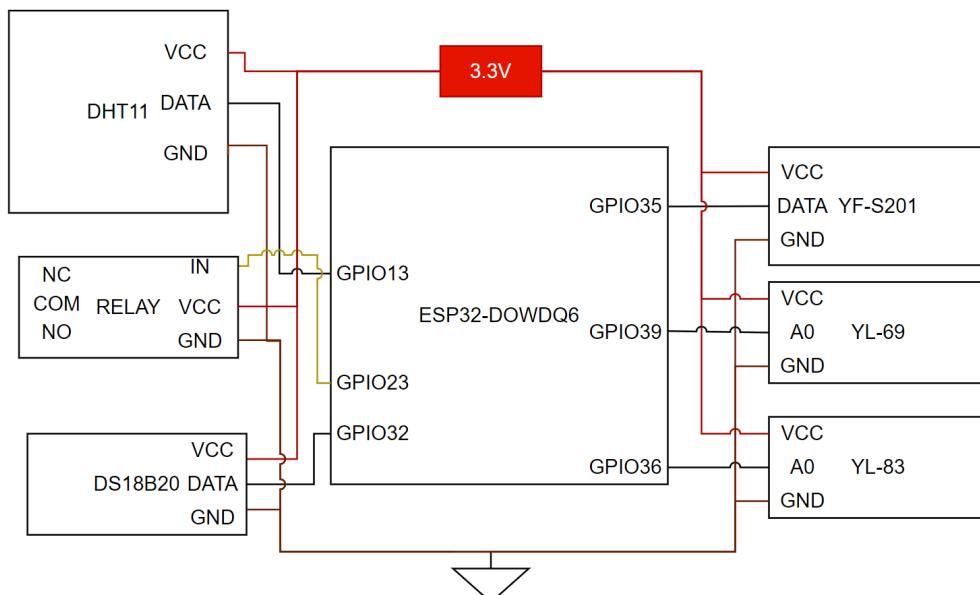


Figure 3.3: ESP32 pinout and connections

The communication between the gateway ESP32 and the Raspberry Pi is done using UART (Universal Asynchronous Receiver-Transmitter) protocol. The gateway ESP32 receives data from the nodes using LoRa radio communication and sends it to the Raspberry Pi using UART. In the figure below it is described the connection between the ESP32 and the Raspberry Pi.

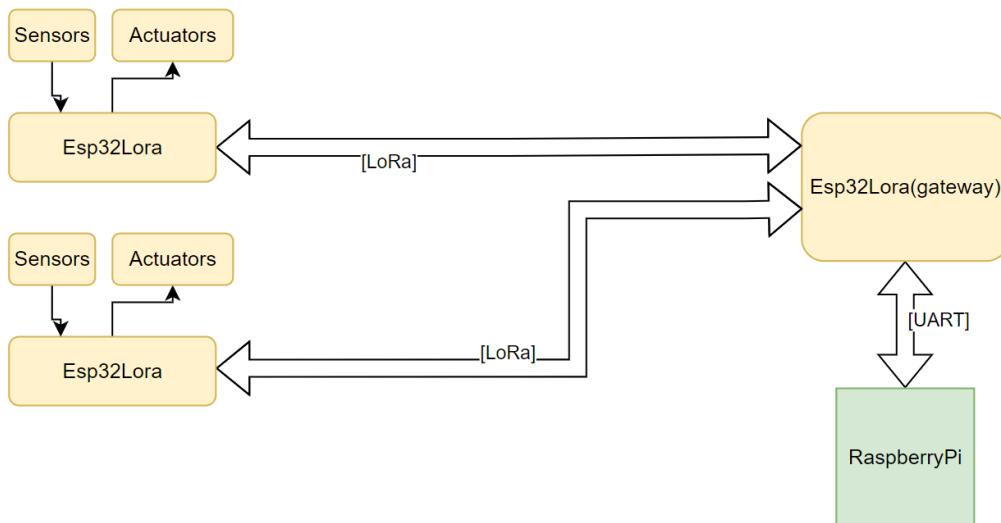


Figure 3.4: ESP32 Gateway connection to Raspberry Pi

3.4 SOFTWARE COMPONENTS

Pilrrigate system contains multiple software components that work together to provide a complete solution. The main sofware components of the Pilrrigate system are: ESP32 firmware, Raspberry Pi script, Web API together with the PostgreSQL database, and Web Application.

3.5 SOFTWARE ARCHITECTURE

The software architecture of the Pilrrigate system is a headless architecure. Headless architecture is a software development approache that separates the frontend and backend of an application, allowing for faster development and better customization [10].

Excluding the necessary code for the firmware running on the ESP32 nodes and the python script running on the RaspberryPi, the code can be divided into 2 main components: Frontend and Backend. Both backend and frontend architectures are layer based, with each layer having a specific role in the system. The backend is divided into 5 layers: Api, Service, Data, Models and Integration.

The Api layer is responsible for exposing endpoints, handling HTTP requests, performing input validation, and returning responses to the client. It represents the entry point of the backend application[11]. The service layer is the one that contains the bussiness logic of the application and is responsible for processing the data received from the Data layer and returning it to the Api layer. Data layer's only role is to interact with the database. It is responsible for data access and persistence and it is the only layer that interacts with the database as any other layer should not be aware of the database and should interact with the database only through the Data layer. Models layer is responsible for defining the data structures used in the application. The integration layer is responsible for integrating with external services, such as Azure IoT Hub and SignalR.

The frontend is also divided into 5 layers: Presenation, State, Services, Models and

Guards. The Presentation layer is responsible for rendering the user interface and handling user interactions. The State layers is responsible for storing the application state and managing the data flow between the components [12]. Service layers is responsible for interacting with the backend API and providing ready to use data to the Presentation layer. Models layer, similar to the backend Models layer is responsible for defining the data structures used in the application[13]. Routing layer manages the navigation between different components[14] and the Guards layer makes sure that the user has the necessary permissions to access a specific route or component[15]. In the following figure, you can see the software architecture of the Pilrrigate system.

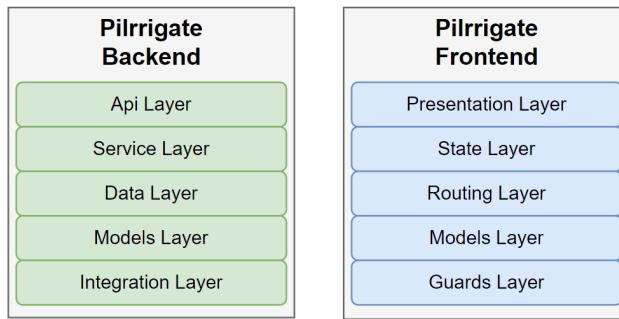


Figure 3.5: Pilrrigate Software Architecture

3.6 DATA FLOW

The data flow in the Pilrrigate system is as follows: Data is collected from the sensors connected to the ESP32 nodes. Then the data is sent to the gateway via LoRa radio communication. The gateway transmits the data to the Raspberry Pi using UART protocol and the Raspberry Pi send the data to Azure IoT Hub using MQTT protocol. The Web API receives the data from the Azure IoT Hub and stores in the PostgreSQL database and send the data to the web application using SignalR. Then the web application displays the data to the end user in real-time. The data flow is illustrated in the figure below:

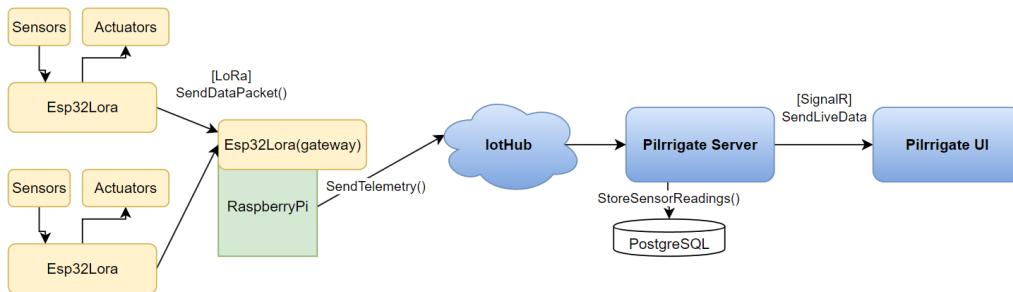


Figure 3.6: Pilrrigate System overview

4. IMPLEMENTATION

4.1 OVERVIEW

This chapter describes the implementation of the Pilrrigate system. If the previous chapters described the architecture and the main components of the system, this chapter focuses on how these components are implemented in practice. The implementation is divided into several sections, each focusing on a specific aspect of the system.

4.2 ESP32 FIRMWARE

For the ESP32 development I had to choose between two main frameworks: ESP-IDF and Arduino. I chose the Arduino framework because it is more user-friendly. As IDE I used Platform IO, which is a VSCode extension that allows to develop on many different platforms, including the ESP32[16].

4.2.1 DATA ACQUISITION

The data acquisition is done using the ESP32 nodes that collect data from the sensors. For each sensor type, I created a specific library that can be used to read the data from the sensor. Temperature and humidity data is collected using a DHT11 sensor. The communication with the sensor is done using 1-wire digital interface which involves 3 main steps[17]:

1. The microcontroller initiates communication by sending the start signal. The start signal is an 18 ms LOW signal followed by a 20–40 μ s HIGH signal.
2. The sensor responds a fixed LOW and HIGH handshake pattern, indicating that it is ready to send data. Usually the acknowledgment is a 80 μ s LOW signal followed by a 80 μ s HIGH signal.
3. After the handshake, the sensor sends a 40-bit data stream, which includes the humidity and temperature data. The bits are sent in a specific order: first the humidity data (16 bits), then the temperature data (16 bits), and finally a checksum (8 bits). Each bit is sent as a 50 μ s LOW signal followed by a HIGH signal that lasts for either 26–28 μ s (for a 0 bit) or 70 μ s (for a 1 bit). In code, for each bit, the microcontroller waits for the LOW signal to start, then waits for 30 μ s then if the signal is HIGH, the bit is a 1, otherwise it is a 0. The checksum is used to verify the integrity of the data received from the sensor.

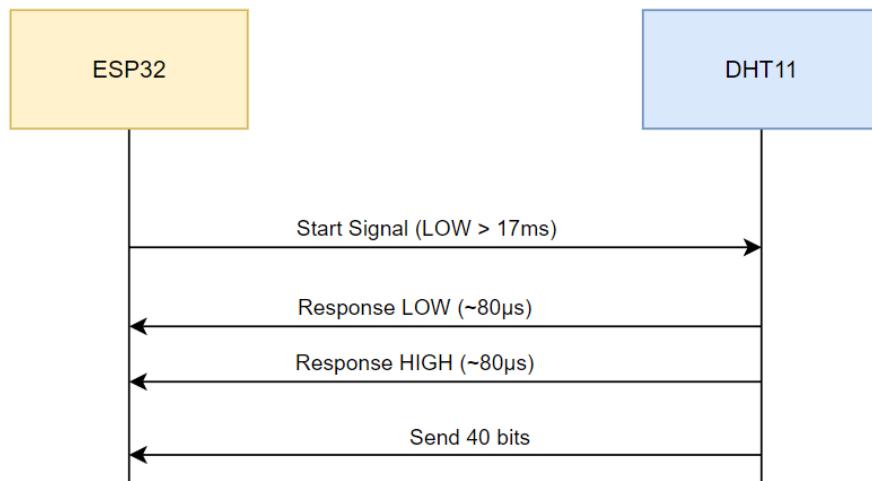


Figure 4.1: Steps in data acquisition from DHT11 sensor

For the soil moisture data acquisition, I used a resistive soil moisture sensor. The principle of operation is based on measuring the resistance of the soil. The sensor consists of two probes that are inserted into the soil. When the soil is dry, the resistance between the probes is high, and when the soil is wet, the resistance is low[18]. Then an ADC is used to measure the voltage across the probes, which is transofmerd into digital value. In this case, the ADC is a 12-bit ADC, which means that the digital value can range from 0 to 4095.

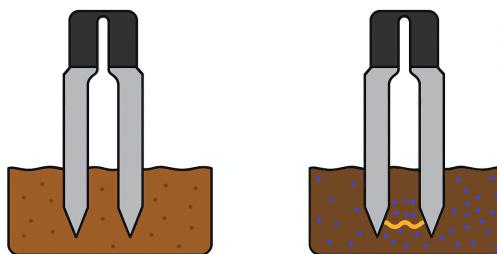


Figure 4.2: Soil moisture sensor based on resistive principle

The raindrop data is collected using a resistive raindrop sensor. The principle of operation is similar to the soil moisture sensor, but in this case, the sensor consists of a plate with two conductive traces that are separated by a small gap. When the rain falls on the plate, it closes the gap and allows the current to flow between the traces. The is connected to an ADC which measures the voltage across the traces.

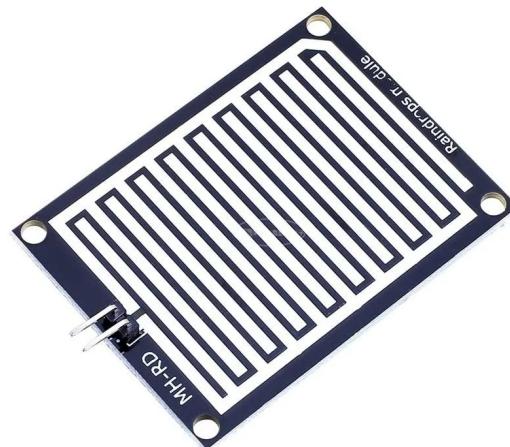


Figure 4.3: Raindrop sensor based on resistive principle

Since the water consumption is a very important aspect in agriculture, I wanted to add a water flow sensor to the system. For the purpose of this project I used an YF-S201 water flow sensor, which is a low-cost sensor that can be used to measure the flow rate of water in a pipe. The sensor consists of a plastic body with a turbine inside that rotates when water flows through it. The rotation of the turbine generates a pulse signal that can be used to measure the flow rate of water. The sensor has a maximum flow rate of 30 liters per minute and a minimum flow rate of 1 liter per minute. The sensor has three wires: red (VCC), black (GND), and yellow (signal). At each rotation of the turbine, the sensor generates a pulse signal on the signal wire. This sensor will be used to check if the irrigation system is working properly or not. The ESP32 counts the number of pulses in a given time interval (e.g., 1 second) to calculate the flow rate. The flow rate can be calculated using the following formula:

$$\text{Flow Rate} = \frac{\text{Number of Pulses} \times 60}{\text{Time Interval (seconds)}} \quad (4.1)$$



Figure 4.4: Water flow sensor used in Pilrrigate

In my implementation the water source is a water tank that will be connected to the irrigation system. The tank will be equipped with a water temperature sensor. The purpose of monitoring the water temperature is to ensure that the water is not too cold or too hot for the plants. The water temperature sensor is a DS18B20 sensor, which is a digital temperature sensor that can be used to measure the temperature of liquids. The DS18B20 sensor uses the 1-wire digital interface to communicate with the ESP32. The sensor can measure temperatures from -55°C to +125°C with an accuracy of $\pm 0.5^\circ\text{C}$.



Figure 4.5: DS18B20 water temperature sensor used in Pilrrigate

To be able to locate each node in the field, a GPS module is used. More precisely, I used a NEO-6M GPS module which is integrated in the LILYGO Meshtastic AXP2101 T-Beam V1.2 ESP32 LoRa development board.

4.2.2 DATA TRANSMISSION

Once the data is collected from the sensors, it needs to be transmitted to the gateway. The ESP32 nodes use LoRa communication to send the data to the gateway. The sensor reading has a period of 10 seconds, which is the default value and it can be changed from the Web Application. The data collected from the sensors is serialized into a sensor reading structure, which is then included in a LoRa packet structure that will be binary serialized and sent over LoRa radio communication.

Listing 4.1: LoRa packet structure

```
1 struct LoRaPacket {  
2     int packetCount;      // Packet count for tracking  
3     SensorData sensorData; // Sensor data to be sent  
4     int stationMac[6];    // MAC address of the device
```

5 } ;

Listing 4.2: Sensor reading structure

```
1 struct SensorData {  
2     time_t timestamp;  
3     float temperature;  
4     float humidity;  
5     float soilMoisture;  
6     float rainLevel;  
7     float waterTemp;  
8     float totalWaterFlow;  
9     float longitude;  
10    float latitude;  
11};
```

All the values regarding the environmental data represent the raw voltages read from the sensors. I chose to sent the raw values, because they can be used to calculate any related values in the web api. This allows a better flexibility in the future.

4.3 RASPBERRY PI AND ESP32 GATEWAY

The gateway ESP23 acts like a proxy between the nodes and the Raspberry Pi. It receives the LoRa packets from the nodes, and then it sends the data to the Raspberry Pi using Serial communication by UART.

UART is an integrated circuit that plays the most important role in serial communication. It contains a parallel-to serial converter and a serial-to-parallel converter[19] [20]. The parallel-to-serial converter is used for data sent from Raspberry Pi to the ESP32, and the serial-to-parallel converter is used for data sent from the ESP32 to the Raspberry Pi. The UART frame format is as follows:

- Start bit: 1 bit, always 0
- Data bits: 5 to 9 bits, usually 8 bits
- Parity bit: 1 bit, optional, used for error detection
- Stop bit: 1 or 2 bits, always 1
- Idle bit: 1 bit, always 1

4.4 WEB API

4.4.1 WEB API

The web API is developed in .NET and it is responsible for user management, data storage, and communication with the IoT Hub. It uses Entity Framework Core to interact with the PostgreSQL database and SignalR to provide real-time communication. It uses the controller pattern to handle the HTTP requests. I created a controller for each resource in the system, such as users, zones, data, devices, schedules and cloud to device messages.

Zone Controller

Since the first step in the activation process is to verify the code entered by the user, I will start describing the zone controller. Using this controller, the user can create a zone, activate a zone, get the IoT Device connection string, retrieve all zones, get a zone by id, and delete a zone. For the database interaction, I created a zone repository that implements the IZoneRepository interface.

Listing 4.3: Zone Repository interface

```
1 public interface IZoneRepository
2 {
3     public Task<bool> CreateZone(Zone zone);
4     public Task<bool> UpdateZone(Guid Id, string Name, Guid userId);
5     public Task<bool> DeleteZone(Guid Id);
6     public Task<Zone> GetZoneById(Guid Id);
7     public Task<Zone> GetZoneByName(string name);
8     public Task<IEnumerable<Zone>> GetAllByUserId(Guid Id);
9 }
```

The controller is also using the IoTDeviceManager service to manage the IoT devices in Azure IoT Hub, which implement the IIoTDeviceManager interface and is responsible for creating, deleting, and checking the existence of IoT devices.

Listing 4.4: IoT Device manager interface

```
1 public interface IIoTDeviceManager
2 {
3     public Task<bool> CreateIoTDevice(string zoneId);
4     public Task<string> GetDeviceConnectionString(string zoneId);
5     public Task<bool> DeviceExists(string zoneId);
6     public Task<bool> DeleteIoTDevice(string zoneId);
7 }
```

4.4.2 ZONE ACTIVATION

The Raspberry Pi represents a "zone" in the system and it connects to a single Azure IoT Hub Device. Each zone needs to connect to the Azure IoT Hub Device using a connection string. To obtain that connection string, a request is sent to the web API to create a new zone. The web api will create the zone in the database and it will create a new IoT Device in the Azure IoT Hub. The connection string will be returned to the "zone". After that, the RaspberryPi won't send any reading to the cloud, the sending of the data will be done only when the zone is activated. The activation process is as follows:

1. The user enters the code displayed on the Raspberry Pi OLED display in the web application.
2. The web application sends the code to the web API.

3. The web API verifies the code and activates the irrigation zone.
4. The web API sends a message to the IoT Device to activate the irrigation zone.
5. The Raspberry Pi receives the message from Azure IoT Hub and activates the irrigation zone.
6. The Raspberry Pi sends a message to the ESP32 nodes to start collecting data from the sensors.

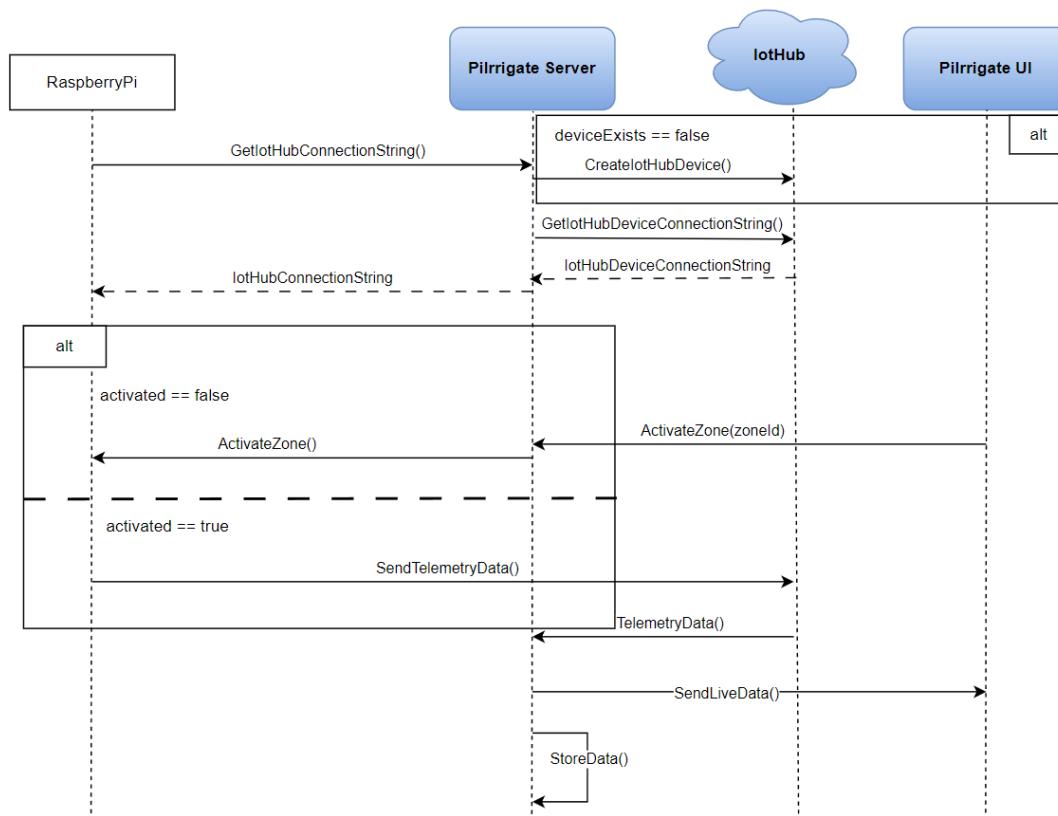


Figure 4.6: Zone activation process

Data Controller

The data controller is used to retrieve stored data from the Web API. This data is stored in the PostgreSQL database and it will be used to display historical data and analytics in the web application. It provides endpoints for:

- Get all data for a zone, including the data for all devices in that zone.
- Get data for a certain period of time.
- Get all data for a device.
- Get data for a device for a certain period of time.

IData repository is used to interact with the database and it implements the IRepository interface.

```
1 public interface IDataRepository
2 {
3     public Task StoreData(SensorReading sensorReading);
4     public Task<IEnumerable<SensorReading>> GetTimedZoneData(DateTime
5         from, DateTime to, Guid zoneId);
6     public Task<IEnumerable<SensorReading>> GetTimedDeviceData(DateTime
7         from, DateTime to, Guid zoneId, string deviceId);
8     public Task<IEnumerable<SensorReading>> GetAllZoneData(Guid zoneId);
9     public Task<IEnumerable<SensorReading>> GetAllDeviceData(Guid zoneId
10         , string DeviceId);
11 }
```

Device Controller

The device controller is used to manage the devices in the system. It provides endpoints for:

- Get all devices for a zone.
- Get all devices for a user.
- Get a device by id.
- Get a device by MAC address.
- Register a new device.

C2D Controller

The C2D (Cloud to Device) controller is used to manage the cloud to device messages in the system. It provides only one endpoint to send a message to a device. The endpoint accepts a C2DMesageRequest object, which contains the zonId, and an object of type C2DMethodCall, which contains the the devicId, the method name, and a list of parameters.

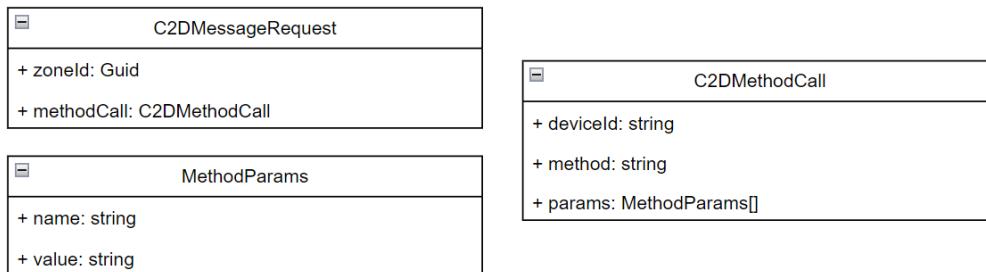


Figure 4.7: C2D Message Request object

Schedule Controller

The schedule controller is used to manage the irrigation schedules in the system. It provides endpoints for:

- Get all schedules.
- Get a schedule by id.
- Create a new schedule.
- Update an existing schedule.
- Delete a schedule.

The Schedule object is defined as follows:

Schedule	ScheduleStatus
+ Id: Guid + Request: C2DMesageRequest + StartTime: DateTime + Duration: TimeSpan + Interval: TimeSpan + EndTime: DateTime + ScheduleStatus: ScheduleStatus (Enum)	NotStarted Running Paused Completed Failed

Figure 4.8: Schedule object

1. The Id is a unique identifier for the schedule.
2. The Request is an object of type C2DMesageRequest that contains the zoneId, deviceID, method name, and parameters.
3. The StartTime is the time when the schedule should start.
4. The EndTime is the time when the schedule should end.
5. The Interval is the time interval between two consecutive executions of the schedule.
6. The Duration is the duration of the schedule execution.
7. The ScheduleStatus is the status of the schedule, which can be NotStarted, Running, Paused, Completed, Failed.

The user can create a new schedule using the UI of the web application, which will send a request to the web API to create a new schedule. The web API will validate the request and create a new schedule in the database. A background service will be used to check and execute the schedules. The background service will run every minute and check if there are any schedules that should be executed or stopped. To be more robust, the duration of the schedule, as well as the start and end time, will be sent to the Raspberry Pi, which will also check if the schedule should be executed or stopped. This way if the Web API or the network connectivity is down, the Raspberry Pi will still be able to execute the schedules.

A background service is used to check the schedules. A background service is a service that implements the IHostedService interface and runs tasks in the background. It is

used to perform long-running tasks and it implements the StartAsync and StopAsync methods [21].

User Controller

As the user needs to be authenticated to access the web API, I created a user controller that handles user registration and login.

For accessing the user data, UserRepository is used, which implements the IUserRepository interface. The authorization is done using JWT tokens, which are generated when the user logs in. To handle all the logic related to JWT tokens, I created a JWT service that implements the IJwtService interface. Besides IUserRespository, and IJwtService, the UserService is also using IPasswordHasher to hash the user passwords. This provides abstraction for hashing and verifying passwords, allowing for easy integration with different hashing algorithms. For the moment, the implementation uses SHA256 hashing algorithm, but it can be easily changed to any other algorithm. In the future, I plan to replace this with Microsoft.AspNetCore.Identity, which provides a more secure and flexible way to handle user authentication and authorization and it is widely used in the .NET community.

Listing 4.5: User Repository interface

```
1 public interface IUserRepository
2 {
3     Task<User> GetByIdAsync(Guid id);
4     Task<User> GetByEmailAsync(string email);
5     Task<IEnumerable<User>> GetAllAsync();
6     Task<bool> CreateAsync(User user);
7     Task<bool> UpdateAsync(User user);
8     Task<bool> DeleteAsync(Guid id);
9 }
```

Listing 4.6: JWT Service interface

```
1 public interface IJwtService
2 {
3     string GenerateJwtToken(User user);
4     bool ValidateToken(string token);
5 }
```

Listing 4.7: Password Hasher interface

```
1 public interface IPasswordHasher
2 {
3     string HashPassword(User user, string password);
4     bool VerifyPassword(User user, string hashedPassword, string
5         providedPassword);
6 }
```

Registration Flow

The registration flow is as follows:

1. The user fills the registration form in the web application.
2. The web application sends the request to the web API. More specifically, it sends a POST request to the register endpoint of the user controller. The controller receives the request as an object of type RegisterRequest.
3. The request is being validated by the web API.
4. If the request is valid, the web API creates a new user in the database
5. The web API generates a JWT token and it sends back an object of type AuthResult.
6. The web application receives the AuthResult object and stores the JWT token in the local storage.

The registration flow is shown in the figure below.

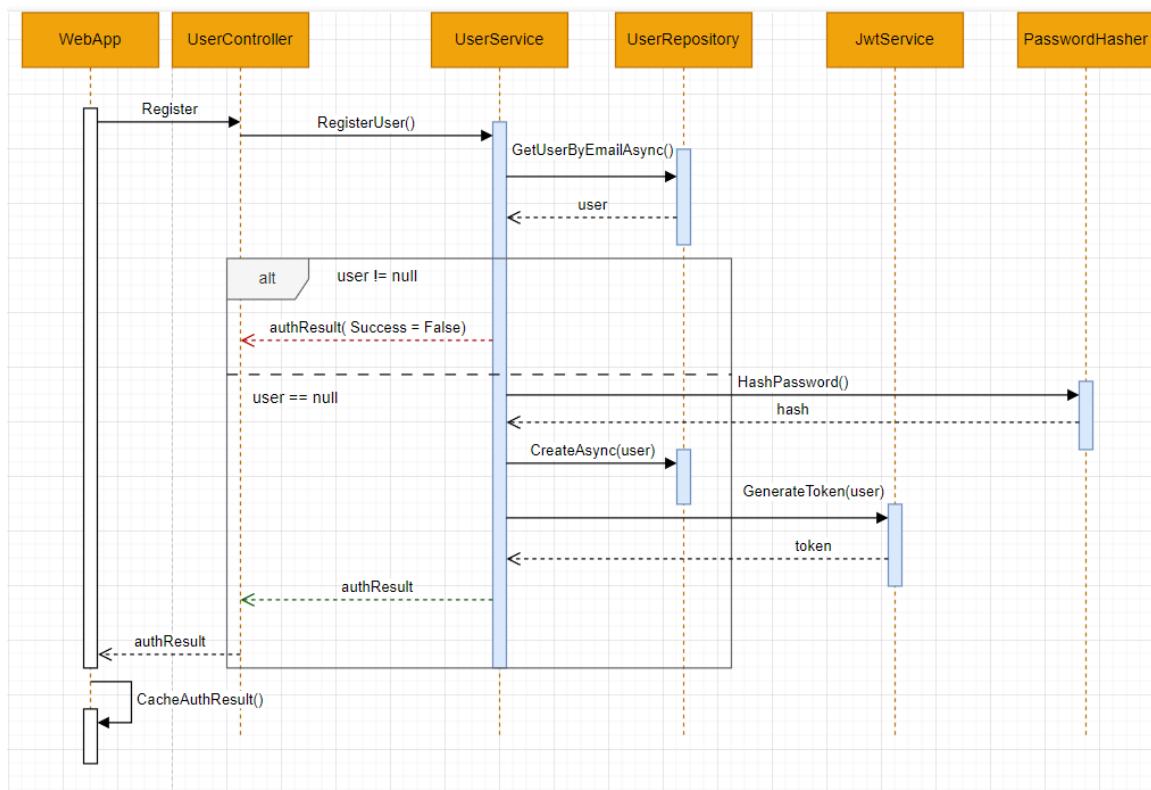


Figure 4.9: Registration flow

The `AuthResult` object and the `RegisterRequest` object are defined as follows:

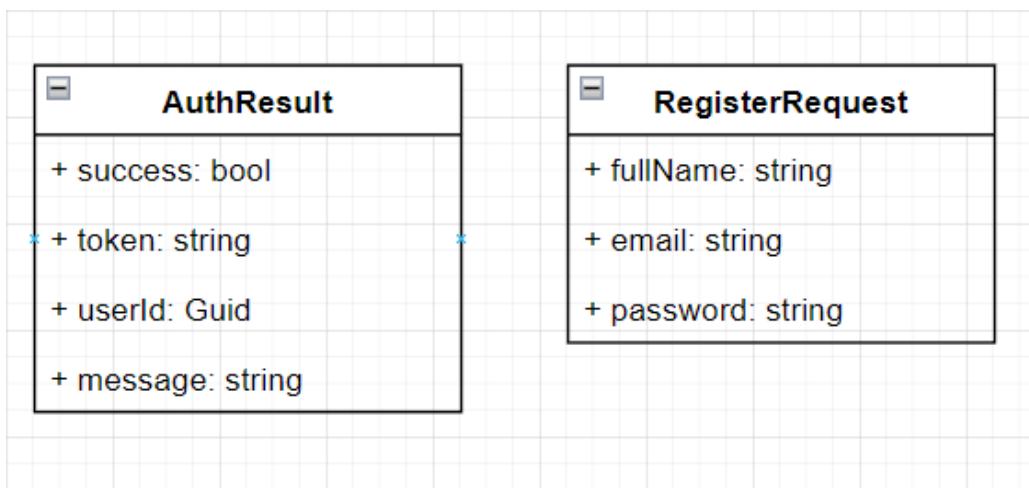


Figure 4.10: AuthResult and RegisterRequest objects

Login Flow

The login flow is similar to the registration flow, but it does not create a new user. The login flow is as follows:

1. The user fills the login form in the web application.
2. The web application sends a POST request to the login endpoint of the user controller. The controller receives the request as an object of type LoginRequest.
3. The request is being validated by the web API.
4. If the request is valid, the web API checks if the user exists in the database.
5. If the user exists, the web API verifies the password and generates a JWT token.
6. The web API sends back an object of type AuthResult.
7. The web application receives the AuthResult object and stores the JWT token in the local storage.

The login flow is shown in the figure below.

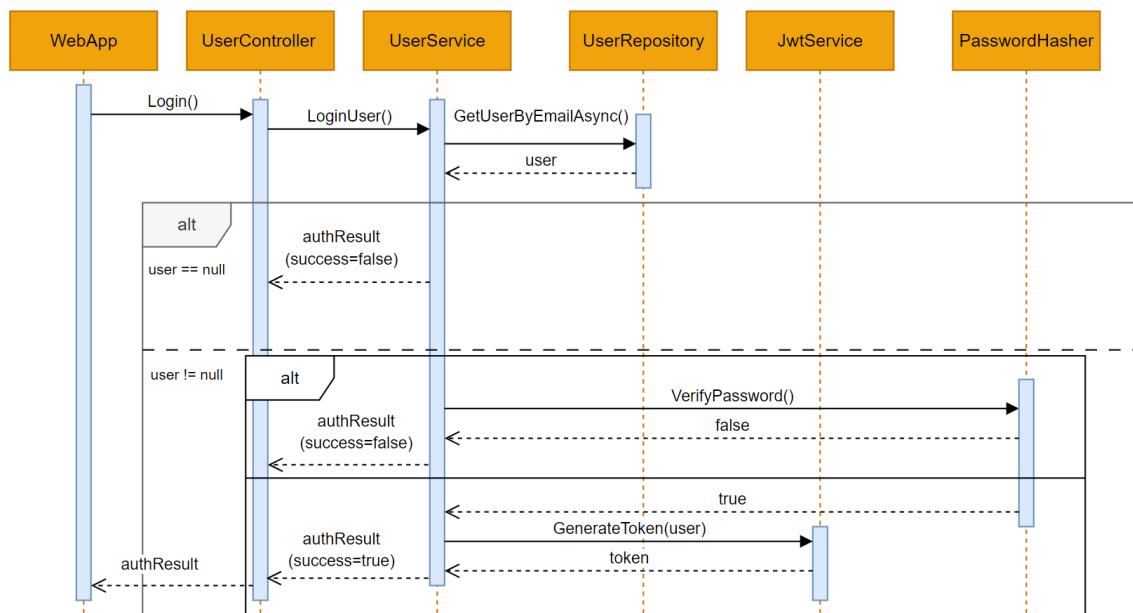


Figure 4.11: Login flow

4.5 WEB APPLICATION

The frontend interface of the smart irrigation system was implemented using Angular. The web application serves as the main point of interaction between the user and the backend system. It allows the users to monitor the environmental conditions in real-time and manually control irrigation events.

The communication between the frontend and web API is done via 2 methods: HTTP requests - for fetching sensor data, trigger irrigation actions and display system status and SignalR - for sending live data from the API to frontend. In the HTTP requests, a JWT token is included, ensuring secure access to system's features.

The user interface is divided into several key components: Dashboard, Device Management, Schedules, History and Analytics. The dashboard displays current soil moisture, temperature, humidity and water flow rate. These values are received using SignalR. Each value is displayed in a separate gauge-style widget to improve the readability. In this section the user can also control the irrigation system. In Device Management section the user can see its registered devices. In Schedules page the user can see and configure schedules. In the History and Analytics, the user can see the historical data, can generate an CSV format file containing the sensor readings and he can also see graph based on the historical data.

4.5.1 LANDING PAGE

The landing page is the first page that the users sees when they access the web application. It presents the user with a brief introduction into the system and it provides the user with the main features of the system. The page is responsive, meaning that it can be accessed from any device, including mobile phones and tablets. The page contains a scrollable carousel with the main features of the system and a call to action button that redirects the user to the registration page. In the following figure you can see the landing

page on a desktop and on a mobile phone.

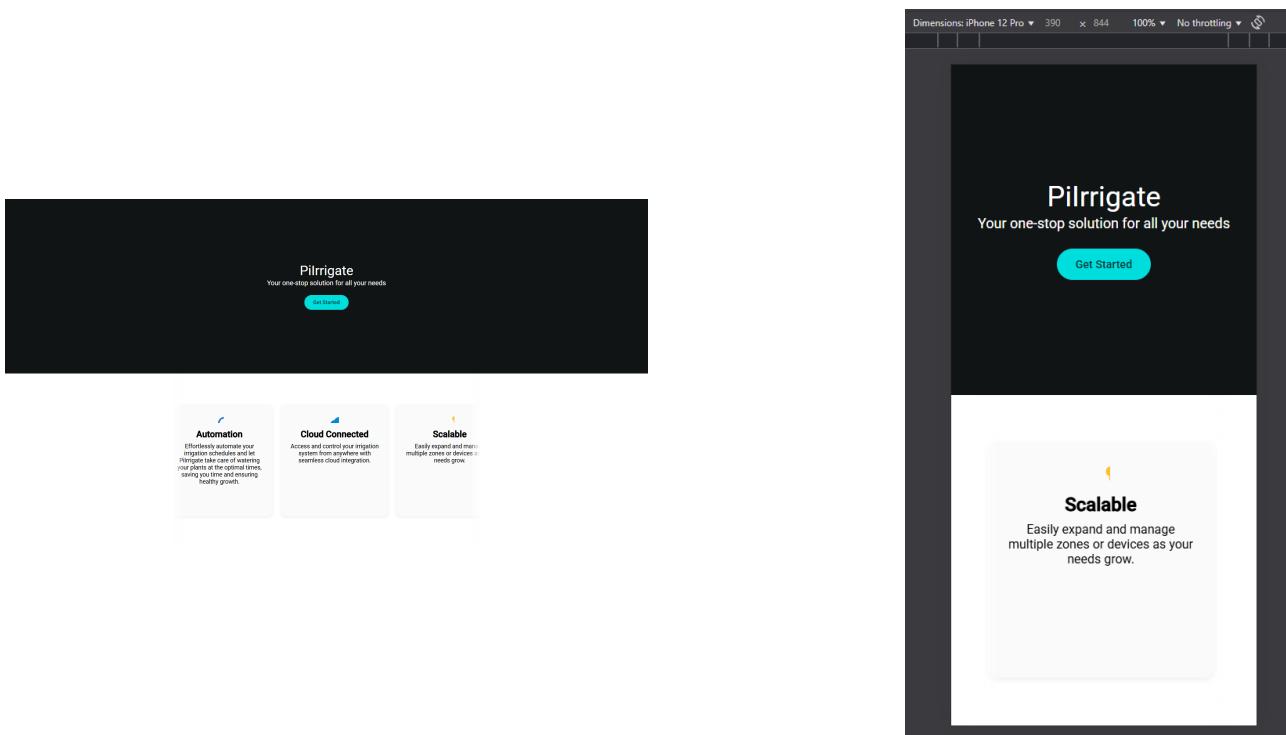


Figure 4.12: Landing page of the web application

4.5.2 REGISTER AND LOGIN

The registration and the Login pages are designed to be as simple as possible. Registration page contains a form with the following fields: Full Name, Email, Password, , Confirm Password and a checkbox for accepting the terms and conditions. The login page contains a form with only 2 fields: Email and Password.

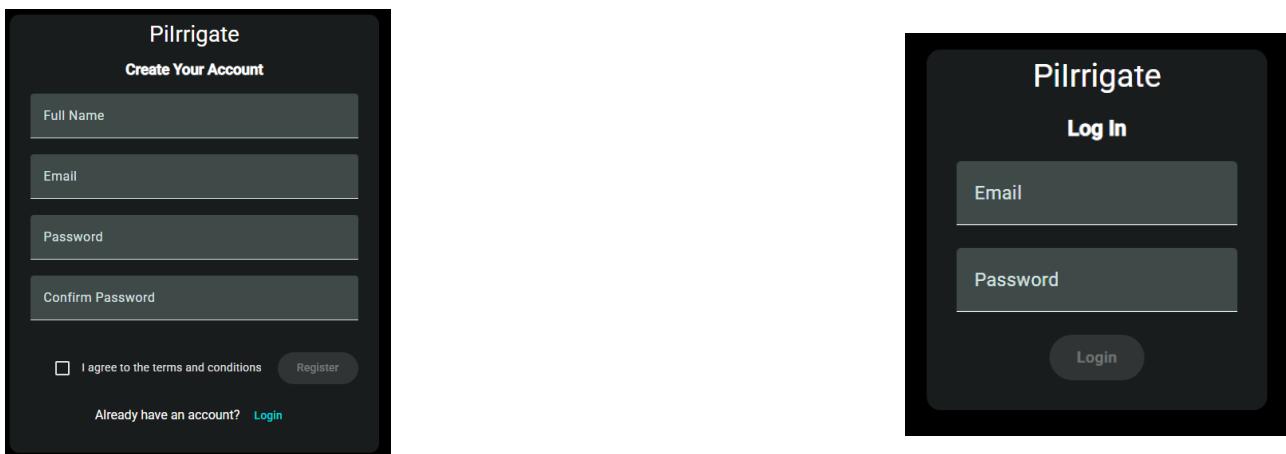


Figure 4.13: Register and Login pages

Now I will describe the registration and login flows. After the user presses the call

to action button from the landing page, he is redirected to the registration page. If the user fills the registration form and presses the register button it will be automatically logged in and redirected to the Dashboard. From the register page he can navigate to the login page where he can login. If the login fails, the user will be able to reset his password and try again. Below is presented the user flow diagram.

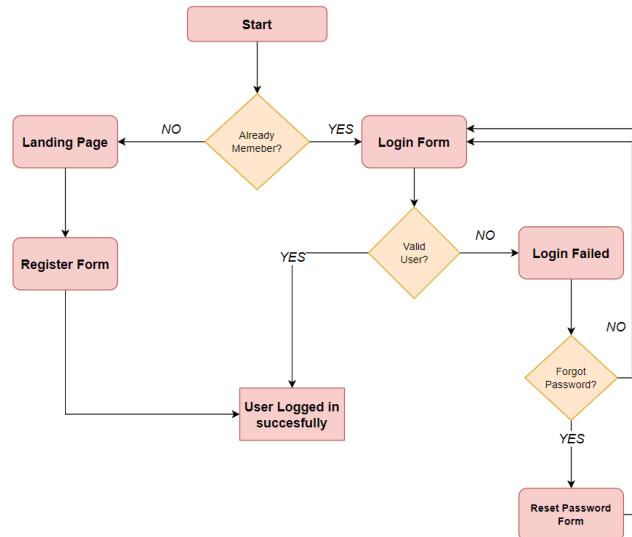


Figure 4.14: User flow

4.5.3 DASHBOARD

The Dashboard components contains several widgets some widgets are used to display live data and others are used to control the irrigation system. The live data widgets are: Live Soil Moisture, Live Temperature, Live Humidity, Live Water Flow Rate and Live Water Temperature. In the control widget, the user can start or stop the irrigation process, and also he can set the data acquisition period.

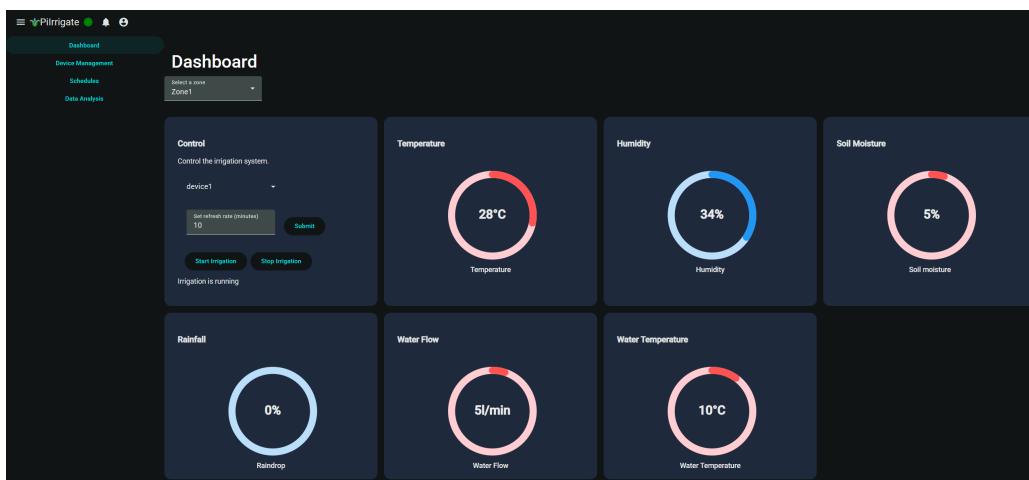


Figure 4.15: Dashboard page of the web application

4.6 RULE BASED SYSTEM

Automation is a key feature of the Pilrrigate system, to achieve this, I implemented a rule-based system that allows the system to make decisions based on the environmental data collected from the sensors.

The rule-based system is implemented in the Web API and it coonsists of the following rules:

1. If the soil moisture is below a certain threshold and the raindrop sensor detects no rain, then start the irrigation.
2. If the soil moisture is above a certain threshold and the water flow rate is above a certain level, the irrigation will be stoped.
3. If the soil moisture reading is not available, then the irrigation will be stopped.
4. If the soil moisture is below the threshold and the water flow rate is zero, then an alert will b sent to the user.
5. If the irrigation process is running and the raindrop sensor detects rain, then stop the irrigation and send an alert to the user.
6. If the water temperature is below or above a certain threshold, stop the irrigation, then send an alert to the user.
7. If the water flow rate remains unchanged for a certain period of time, then send an alert to the user.

This set of rules is executed every time a new sensor reading is received. The rules are implemented in the IrrigaitonManager service which implements the IIrrigationManager interface.

4.7 USED TECHNOLOGIES

4.7.1 OVERVIEW

The Pilrrigate system is build using a variety of technologies, each serving a specific purpose. For programming the ESP32, I used Arduino framework, within the Platform IO IDE. The Raspberry Pi is programemd in Python and it uses Azure IoT SDK for Python to communicate with the Azure IoT Hub. The web API it was developed in .NET 8. The web application is developed in Anguler 19. The live communication between the web API and the web application is done using SignalR. The used database is PostgreSQL.

5. TESTING AND RESULTS

5.1 TESTING

5.1.1 UNIT TESTING

5.1.2 PERFORMANCE TESTING

5.2 RESULTS

5.3 REAL WORLD APPLICATIONS

5.4 FUTURE WORK

5.5 CONCLUSION

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