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CS4390 I Senior Capstone Project

TerraTek

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Abstract

This project presents the development of TerraTek, an IoT-based monitoring system designed to assist a customer in tracking environmental data. The system utilizes Arduino-controlled sensor clusters to gather data on key parameters such as rainfall, water pH, water level, and so on, which are then transmitted to a centralized server. A responsive web interface allows users to visualize data trends and generate reports to aid decision-making processes. Through data analysis, the project demonstrates improved statistics by utilizing historical and real-time data. Future work will involve extending the system's capabilities to include real-time camera monitoring based on sensor data.

Plagiarism Declaration

With the exception of any statement to the contrary, all the material presented in this report is the result of my own efforts. In addition, no parts of this report are copied from other sources. I understand that any evidence of plagiarism and/or the use of unacknowledged third party materials will be dealt with as a serious matter.

Signed

William Kolath

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Software Requirement Specification

1.1 Introduction

1.1.1 Purpose

The purpose of this document is to provide a detailed description of the TerraTek Sensor System (TSS). It will explain the intended scope, purposes and features, constraints, and interactions between its systems. This document is intended for all stakeholders and developers of the system.

1.1.2 Project Scope

The intended scope of the TSS is to provide a web interface for the user to observe telemetry data. Implementing clusters of sensors that will collect and aggregate data to a central database which can be parsed and graphed through a web interface. This will be implemented on small, household scale with the ability to expand to scale.

1.2 Overall Description

1.2.1 Product Perspective

The TSS will encapsulate a backyard consisting of water tanks and garden areas. Both areas will have two sensor clusters each with each cluster collecting data depending on the area. This is a small scale project to serve as a foundation for larger scale implementation.

1.2.2 Product Features

TSS include the five features listed below:

Feature 1: Tank Monitoring

Feature 2: Garden Monitoring

Feature 3: Remote access to data

Feature 4: Data visualizations

Feature 5: Remote camera

1.2.3 User Classes and Characteristics

There are two main classes of users for our project.

- Owner of RWH system
- Other users

The owner of the RWH is primarily focused on being able to understand the current and historical status of the RWH system. They will also use the garden monitoring functionality to make changes to their watering practices as needed. They also must be able to make configuration changes to the TerraTek system to suit their changing needs.
Other users will be primarily focused on learning about how a RWH system works as well as seeing different weather data from the area visualised.

1.2.4 Operating Environment

The server will use Ubuntu Server Version 24.04.1 LTS, the most current version as of writing. The server will utilize MySQL for database operations. The sensors will be programmed with Arduino to communicate with a Raspberry Pi, which will aggregate and send all the data to the server.

1.2.5 Design and Implementation Constraints

A significant portion of the system will be deployed outdoors. Some portion of the system will deployed in water tanks, either submerged or directly above water. Water and weather proofing will be a significant constraint we must work around in this project. Another constraint is longevity. The system needs to be designed to operate for long periods of time without replacing hardware components or performing maintenance on the software.

1.2.6 User Documentation

We will create a user manual for the TerraTek system. There will also be a small online tutorial for users of the website, explaining what the system is monitoring and how to operate the website.

1.2.7 Assumptions and Dependencies

We are making the following assumptions:

- All sensors will be programmable on Arduino
- Each cluster contains only a singular sensor of its type
- The Tanks will never completely empty nor completely fill

We are dependent on the following systems:

- Linux Server
- Home WiFi of the RWH owner
- Pre existing RWH system

1.3 System Features

Feature 1: Tank Monitoring

Each of the RWH tanks on the property needs to be monitored using various sensors. This is a very high priority feature.

REQ-1.1: The system must monitor tank level.
REQ-1.2: The system must monitor tank water PH.
REQ-1.3: The system must monitor tank TDC.
REQ-1.4: The system must monitor tank temperature.

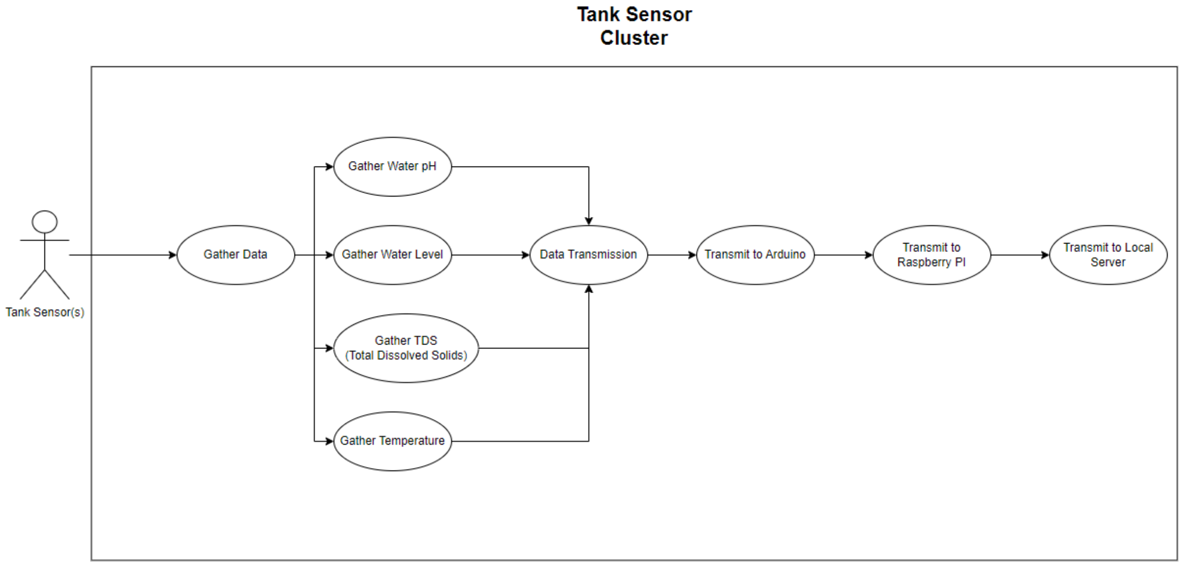

Figure 1.1: Use Case Diagram for Tank Sensors

Feature 2: Garden Monitoring

The garden area will have sensors installed to monitor the health of the soil and current weather conditions. This will allow the owner of the garden to make informed decisions regarding watering and planting. This is a high priority feature.

REQ-2.1: The system should monitor soil moisture in multiple locations of the garden.

REQ-2.2: The system must measure rainfall in the garden.

REQ-2.3: The system should measure atmospheric temperature at multiple locations in the garden.

REQ-2.4: The system should measure atmospheric pressure at multiple locations in the garden.

REQ-2.5: The system could measure wind speed in the garden.

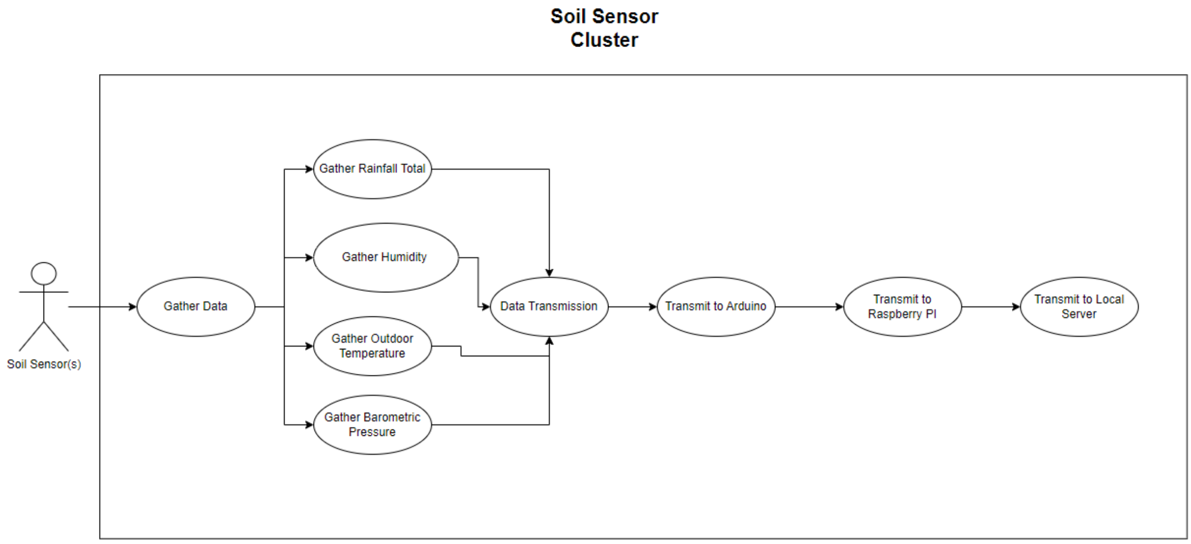

Figure 1.2: Use Case Diagram for Soil Sensors

Feature 3: Remote access to data

Users of the system must be able to access all of the gathered data from anywhere in the world. This feature enables the owner of the RWH system to see its current status even if they are not home. It also allows users interested in leaning about RWH systems to see one in action remotely. This is a very high priority feature.

REQ-3.1: The user must be able to access all current data using a web interface.

REQ-3.2: The user must be able to access historical data using a web interface.

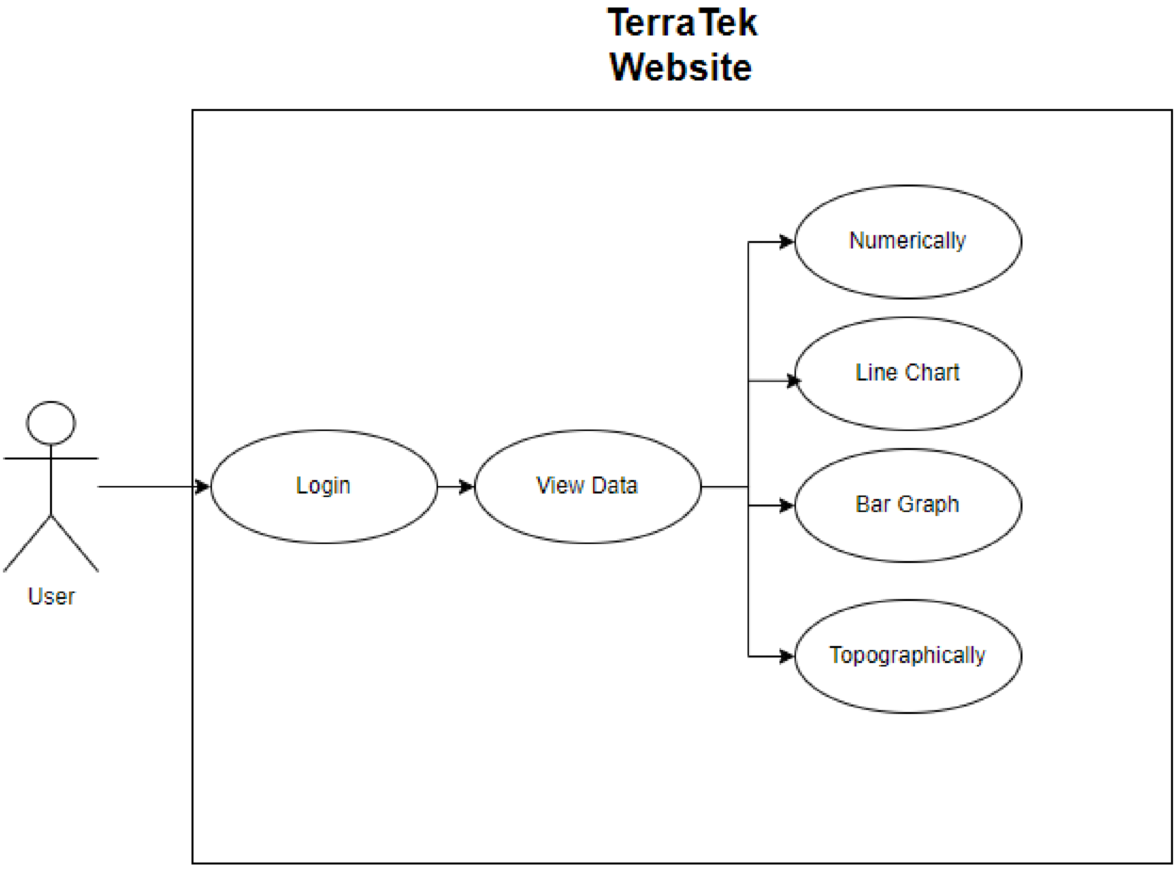

Figure 1.3: Use Case Diagram for Website

Feature 4: Data visualizations

Users of the system should be able to use data visualizations to read current and historical data. This is a medium priority feature.

REQ-4.1: The user should be able to use data visualisations to see current data.

REQ-4.2: The user should be able to use data visualisations to see historical data.

REQ-4.3: The user should be able to run custom reports for user defined sensors and time frames.

Feature 5: Remote camera

Users of the system could be able to show the users live views of the tanks and surrounding property. This enables users interested in RWH systems to actually see one in action. This is a low priority feature.

REQ-5.1: The user could be able to view live images of the tanks

REQ-5.2: The user could be able to view live images of the property

1.4 External Interface Requirements

1.4.1 User Interfaces

Users will interface with the system using a web browser to access the website. The system will support Firefox, Safari, and Chromium based browsers.

1.4.2 Software Interfaces

There will be many software interfaces. The Sensors use many different predefined interfacing protocols such as I2C. The sensor clusters will communicate to the central hub using a wireless data communication standards, such as WiFi or LoRa. The central hub will then send the aggregated sensor data to the server using a standard internet protocols.

1.5 Other Nonfunctional Requirements

1.5.1 Performance Requirements

REQ-6.1: The website must load the homepage in less than 5 seconds

REQ-6.2: The server must be able to handle at least 50 users accessing the website at the same time.

REQ-6.3: The system should be able to create historical reports in less than 10 seconds

REQ-6.4: The system should be built with no dependency on subscription based or free tier cloud services.

1.5.2 Software Quality Attributes

REQ-7.1: The website must be easy to use.

REQ-7.2: The website must remain accessible even if portions of the sensor network fail.

REQ-7.3: The system must be secure

Chapter 2

Software Design

2.1 Research

2.1.1 Arduino Sensors

DFRobot Gravity Analog Electrical Conductivity Meter (DFR0300)

The DFRobot Gravity Analog Electrical Conductivity Meter is designed to measure water's electrical conductivity, providing insight into the dissolved salts and overall water quality. This sensor is particularly useful in applications such as hydroponics and aquarium management. Using the DFRobot Gravity library, developers can easily calibrate the sensor and collect data efficiently, enhancing the user's ability to monitor water quality in real time [16].

Weather Meter Kit (SEN-15901)

The Weather Meter Kit is a comprehensive package that includes sensors to monitor weather conditions, such as wind speed, wind direction, and rainfall. These measurements are essential for setting up weather stations, where real-time data can be analyzed to predict weather trends. Integration with this kit varies depending on the specific sensors, as they may require unique libraries or standard analog and I2C communication protocols to process data accurately [20].

ME007YS Waterproof Ultrasonic Distance Sensor (SEN0312)

The ME007YS is a robust ultrasonic sensor designed for distance measurement in outdoor and industrial environments, even underwater. This sensor operates by emitting ultrasonic waves and capturing reflections. The NewPing library simplifies handling ultrasonic pulses and interpreting distance measurements, making this sensor reliable for applications in challenging environments [2].

Weather-proof Ultrasonic Sensor (SEN0208)

Similar to the ME007YS, the SEN0208 sensor provides reliable distance measurements in outdoor settings and is weatherproof. Utilizing the NewPing library, this sensor is capable of accurate data acquisition in harsh weather, making it suitable for long-term outdoor installations [21].

Waterproof DS18B20 Temperature Sensor Kit (KIT0021)

The DS18B20 is a popular waterproof temperature sensor known for its durability in harsh conditions. Using the OneWire protocol, multiple sensors can connect to a single data pin, a unique feature beneficial for applications requiring distributed temperature monitoring. The DallasTemperature library enables easy data acquisition from this sensor, allowing for seamless integration in temperature-critical monitoring setups [3].

Arduino MKR Environmental Shield (ASX00029)

The Arduino MKR Environmental Shield includes sensors for temperature, humidity, barometric pressure, and light intensity. This shield is particularly suitable for comprehensive environmental monitoring applications. The Arduino-MKRENV library simplifies data handling across multiple sensors, streamlining the process of integrating environmental metrics into projects [18].

Gravity Non-contact Liquid Level Sensor (SEN0204)

This non-contact sensor is ideal for environments where the liquid should not be touched directly, such as in sterile or hazardous conditions. The DFRobot-Sensor library offers straightforward methods for obtaining liquid level data, allowing for quick and safe implementation in sensitive monitoring applications [15].

MODBUS-RTU RS485 4-in-1 Soil Sensor (SEN0604)

This Soil Sensor Provides 4 different data outputs; Soil Moisture, Temperature, PH, and EC. This sensor is also built to last buried in the soil it is measuring, allowing it to be non-invasive and low maintenance. The ArduinoModbus Library allows for straightforward data gathering from the sensor to allow for quick setup and easy deployment. [4]

2.1.2 Website Framework

React.JS

ReactJS is a JavaScript library developed by Facebook for building user interfaces, primarily focused on component-based development, DOM(Document Object Model) manipulation, and various other functionalities [7]. It allows developers to create reusable UI components that handle the view layer of web applications efficiently. React updates and renders only the components that change, which improves performance and user experience. It also features a virtual DOM, which speeds up updates by minimizing direct manipulation of the real DOM.

NextJS

Nextjs is a React-based framework for building web applications [7]. It adds powerful features such as server-side rendering (SSR), static site generation (SSG), and dynamic routing, which enhance performance and SEO(Search Engine Optimization). With Nextjs, developers can render pages on the server before sending them to the client, making the initial load faster and more SEO-friendly. It also integrates well with APIs and data fetching techniques for modern web applications.

2.1.3 LoRaWAN

LoRa

LoRa, which stands for long range, is a wireless transmission protocol designed for long range, low power, applications. LoRa is capable of transmitting up to 5 kilometers in urban environments and up to 10 kilometers in rural environments with line of sight between devices [1]. The reason that LoRa is capable of transmitting such long distances is that it uses a radio modulation technology known as Chirp Spread Spectrum or (CSS) [11]. CSS works by sending series of chirps that encode data. Other radio protocols such as amplitude modulation (AM) and frequency modulation (FM) are highly susceptible to noise and obstructions and require high powered transmission devices to achieve the distances that they do. CSS, on the other hand, is very resilient to noise and obstructions, which makes it an ideal choice for urban environments [22]. The other thing that makes LoRa stand out is its incredibly low power usage. Unlike other radio protocols, it takes very little power to transmit and receive LoRa. This enables the use of batteries and solar in remote end-nodes [17], which makes LoRa a perfect choice for rural and farming applications. This is also what makes LoRa a great choice for our project. LoRa operates on license free sub-gigahertz bands, in the United States a common frequency choice is 915 MHz [14]. This means that there fewer costs and complexity that would be associated with operating on other bands. The major drawback to LoRa is data transmission rates, you can expect to see transmission speeds ranging from 250bit/s to 11kbit/s, however, for end nodes collecting data every couple of minutes this does not pose a significant issue [8].

LoRaWAN

LoRaWAN acts as a media access control (MAC) layer for the end nodes on the LoRa network [10]. LoRaWAN is a star network topology with many end nodes connecting to a gateway. Each gateway can support hundreds of devices, depending on how often they transmit data [17]. The gateway is responsible for collecting the packets sent by the end nodes and forwarding them to a network server.

LoRaWAN network server

A network runs software that manages one or more gateways. The network server typically stores the packets it receives from the various end nodes in a database and allows users to integrate their projects with the server. This entire architecture is a star of stars model and allows one network to cover a vast area with many gateways [22]. There are two main categories of networks servers, public and private. The main difference between the two categories is the entity operating the server and how access to the network is configured [5].

Public network servers (such as The Things Network) allow any end node that has been registered with the network to connect to any gateway on the network and have their packets forwarded to the users application. Public servers typically offer a tiered subscription model, many offer a free tier with support for a limited number ov devices and features [12]. It is worth noting that any end node can connect to any gateway, however, only end nodes that have been configured with the same network server will have their packets routed correctly.[10] All communication is encrypted and only the person who registered the end node is able to read the data, even if they do not own the gateway that the end node is connected to [10].

The other type of network servers are private network servers. These servers are hosted by the network owner either locally or on a web hosting platform and allow for more secure and private handling of data [5]. For many beginners, using a public network server is very convenient, all that they need to do is configure their gateway to forward packets to a public server like The Things Network, and they are ready to start connecting their end nodes. It is even possible that someone else nearby has a gateway that can be used instead of acquiring their own gateway. Setting up a private network server is a more complex undertaking and requires setting up a server to run the software that will control the gateways [5]. For this project we will be creating our own private network server to host our application.

ChirpStack

For people wanting to configure their own private network servers, there are several open-source projects that package all the network server components into one place. One of these projects is ChirpStack [19]. ChirpStack even has a dedicated Raspberry Pi OS that is ready to be configured as a network server. ChirpStack also includes a web interface for easy configuration and end node management. Additionally, ChirpStack provides a python package that enables easy integration using the gRPC API [6]. For these reasons, we believe that ChirpStack will work well for our project.

Gateways

As mentioned above, the gateway is responsible for collecting packets from end nodes and forwarding them via the internet to the network server. This typically occurs using UDP or a similar protocol. There are many gateways available with many different applications. One interesting option that we are currently investigating for our project is creating our own gateway using a Raspberry Pi and a gateway hat. These gateway hats, such as Elecrow's LR1302 HAT, connect directly to the Raspberry Pi and allow for a lot of configuration and flexibility [23]. The same Raspberry Pi running the gateway can also run the network server, this is a very compact and elegant solution that offers a lot of flexibility. The main concern is range, this is something that we need to test to determine if it is a viable solution for our project.

End Nodes

There are numerous end nodes that work using LoRa. The one that we have chosen for our project is the Arduino MKR WAN 1310. This board comes with the advantage of having all the support, documentation, and libraries that Arduino provides for all of its products. This board provides an easy way to integrate all the required sensors and connect to a gateway using LoRa [9].

2.1.4 Database

A database solution was required as for the implementation of the TSS would require a way to both store and organize the data collected from all sources.

SQL

SQL was decided as the database solution for this specific implementation. It was chosen as all members were familiar with the language as well as being perfectly suited for processing and storing text outputs collected from sensor data. How SQL expresses data is through mathematical relations [13]. The data collected from the raspberry pi will be expressed as the following relation:

ER Diagram

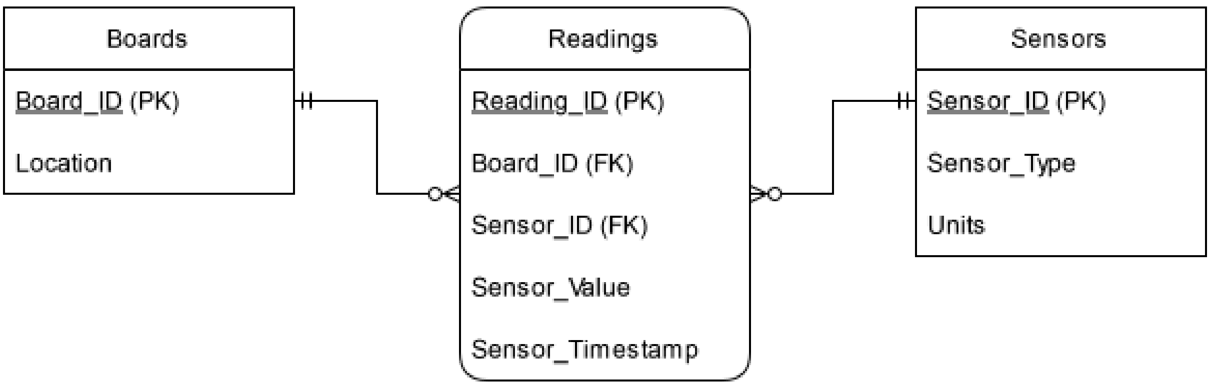

Figure 2.1: ER Diagram

This will serve as our schema for the database. Boards, Sensors and Readings serving as the entities present within. The Sensors table will represent individual sensor readings and the kind of sensor that is reading the data. The Boards table will represent a Cluster of sensors as well as that Cluster's location. Finally the Readings table will take the Board_ID and Sensor_ID from the Boards and Sensors tables in order to express the readings from any given sensor, which Cluster that sensor belongs too, and the time that the sensor has taken that specific reading.

2.1.5 Deployment Location Mapping

Figure 2.2: Water Tank Map

Water Tanks

There are 4 water tank locations as shown above in the photo. The two southern-most are fed by the house, fresh water from the roof catching rain, and gray water from the house appliances after use. The fresh water from the house is used to feed all of the houses water use, and the gray water is used to water plants in the area surrounding the house. The 2 northern tanks are fed by either side of the garage with fresh rainwater, and this water is used mostly to water the gardens they are adjacent to.

Garden Plots

There are many garden plots that we could attempt to gather data on, but the overhead of running so many sensors may prove to be extensive. To mitigate this the project will likely only be working on a select few of the garden plots to gather data. There are 4 raised garden boxes on the northern side of the garage, these 4 are used to grow annual vegetables.

2.2 Diagrams

2.2.1 Use Case Diagram

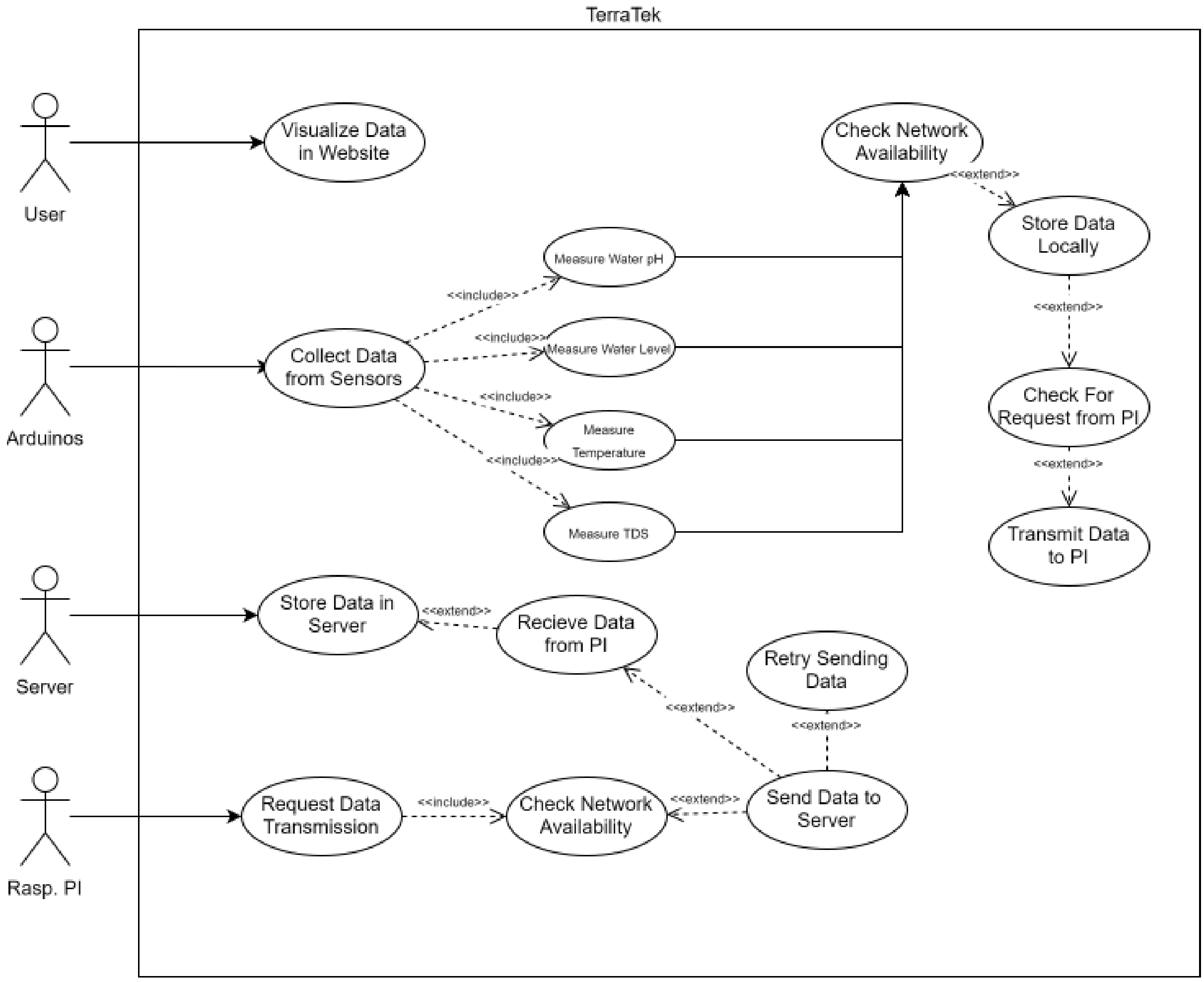

Figure 2.3: Use Case Diagram

2.2.2 Flow Diagram

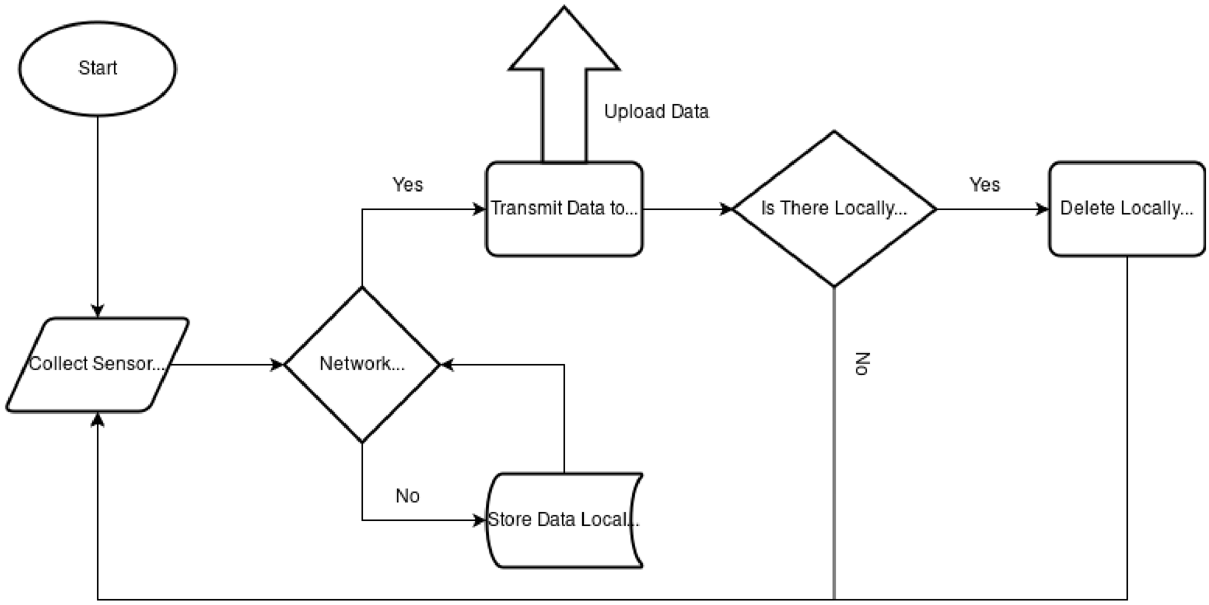

Figure 2.4: Flow Diagram

2.2.3 ER Diagram

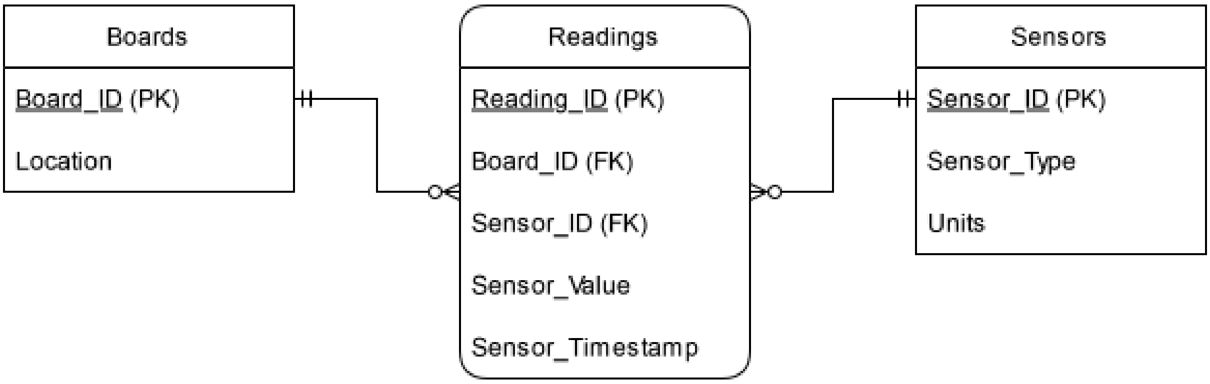

Figure 2.5: ER Diagram

2.2.4 Class Diagram

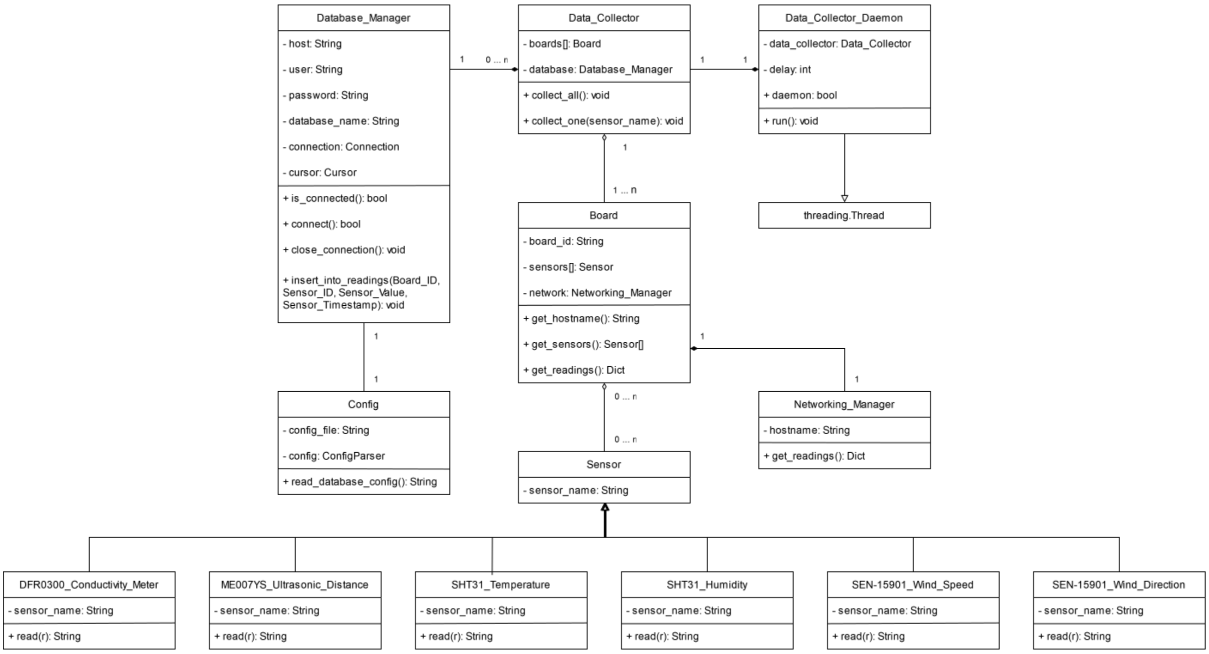

Figure 2.6: Class Diagram (Raspberry Pi)

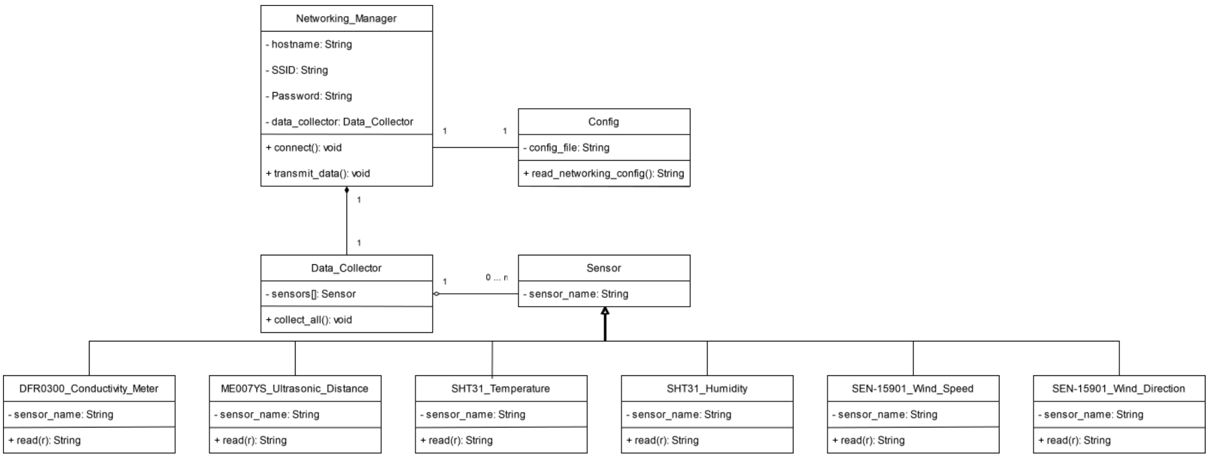

Figure 2.7: Class Diagram (Arduino)

2.2.5 Object Diagram

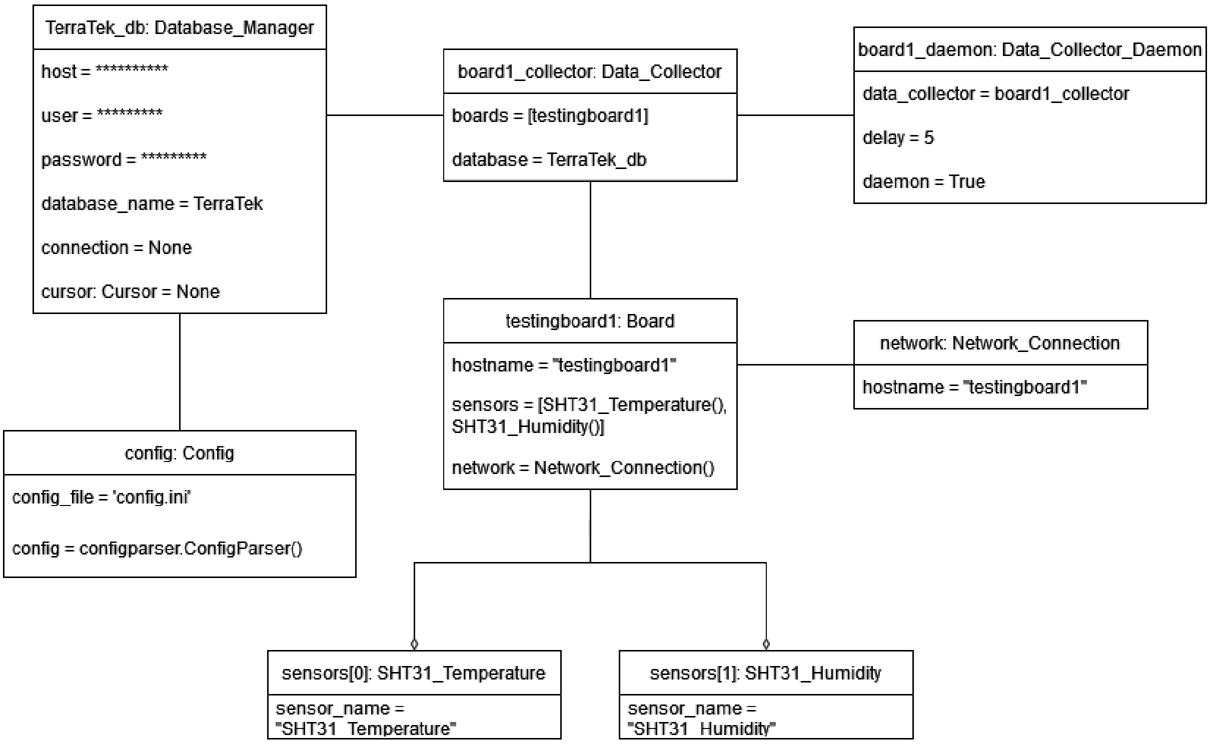

Figure 2.8: Object Diagram

2.2.6 Sequence Diagram

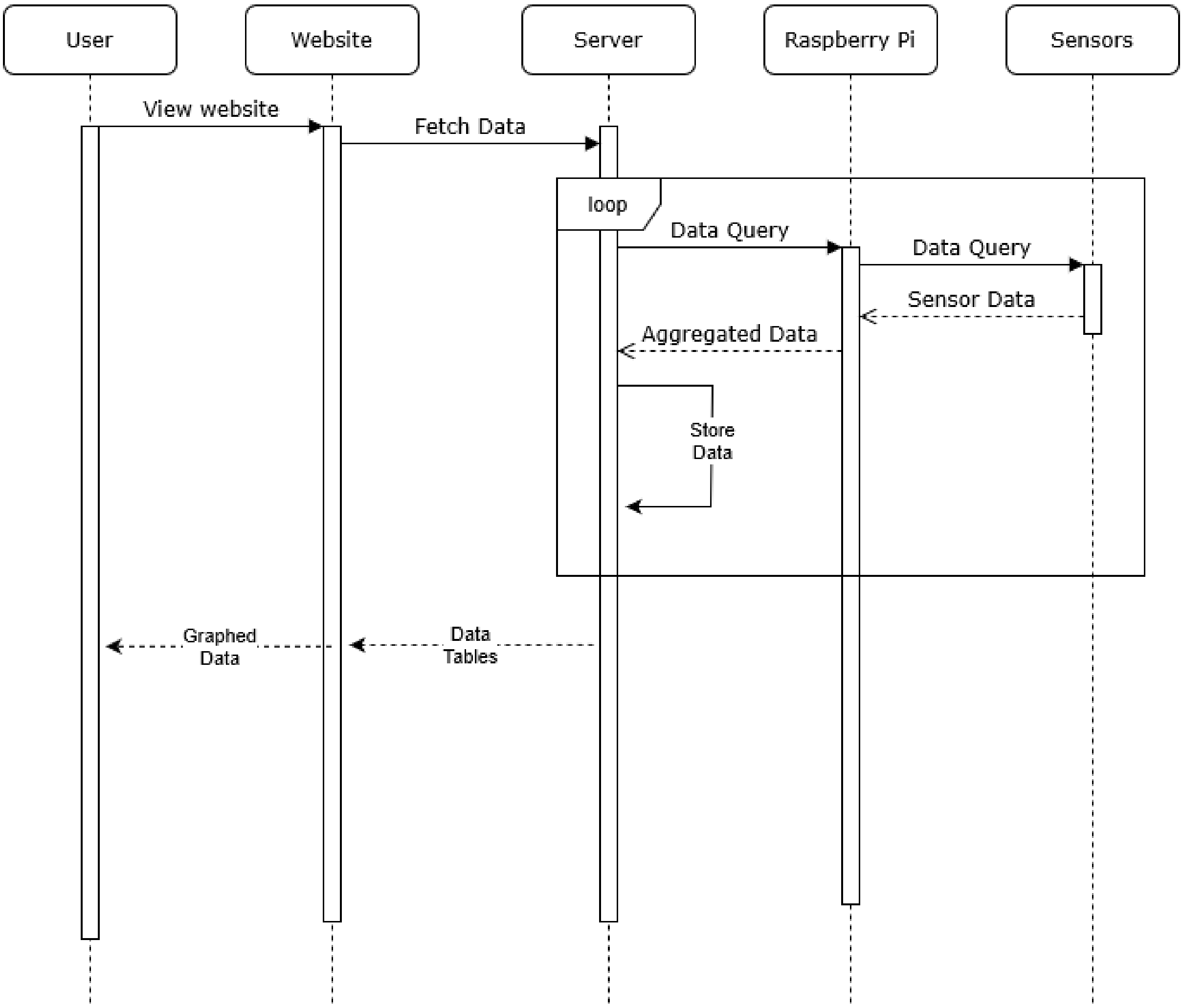

Figure 2.9: Sequence Diagram

2.2.7 DFD Level 0 Diagram

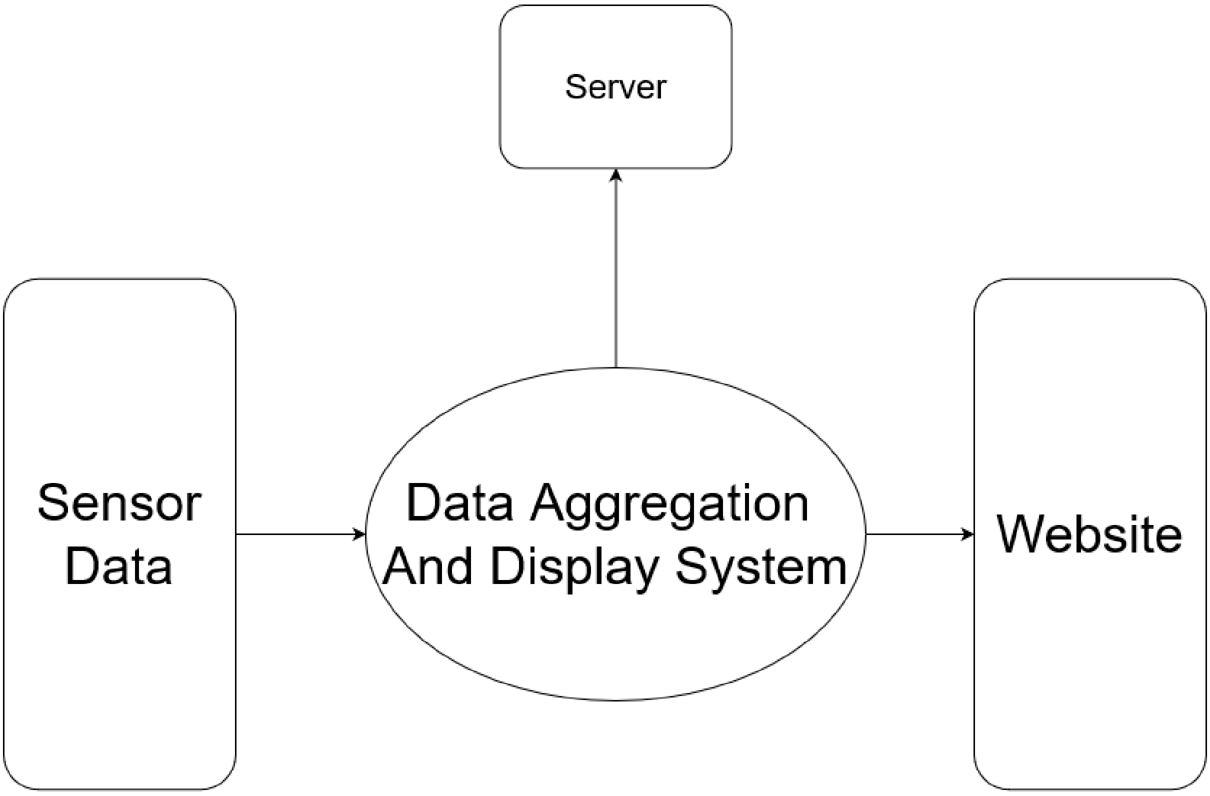

Figure 2.10: Data Flow Diagram Level 0

2.2.8 DFD Level 1 Diagram

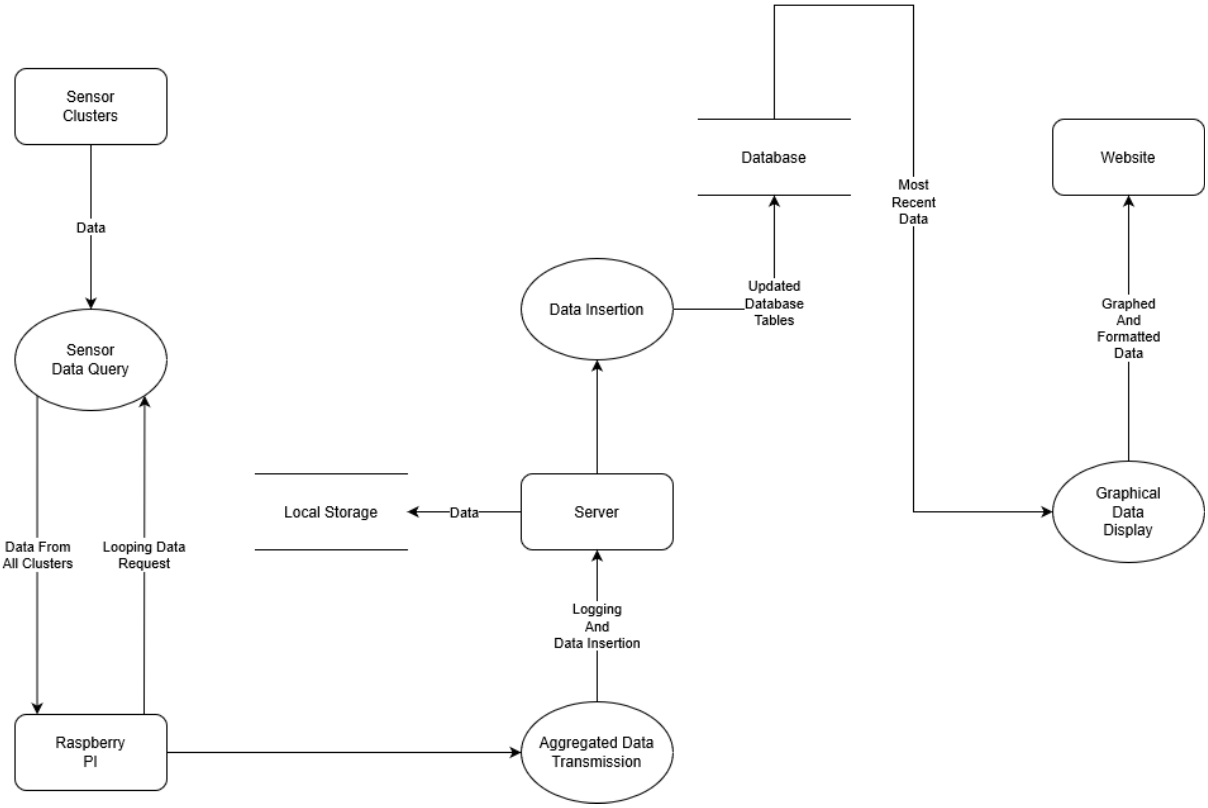

Figure 2.11: Data Flow Diagram Level 1

2.2.9 Raspberry Pi State Machine Diagram

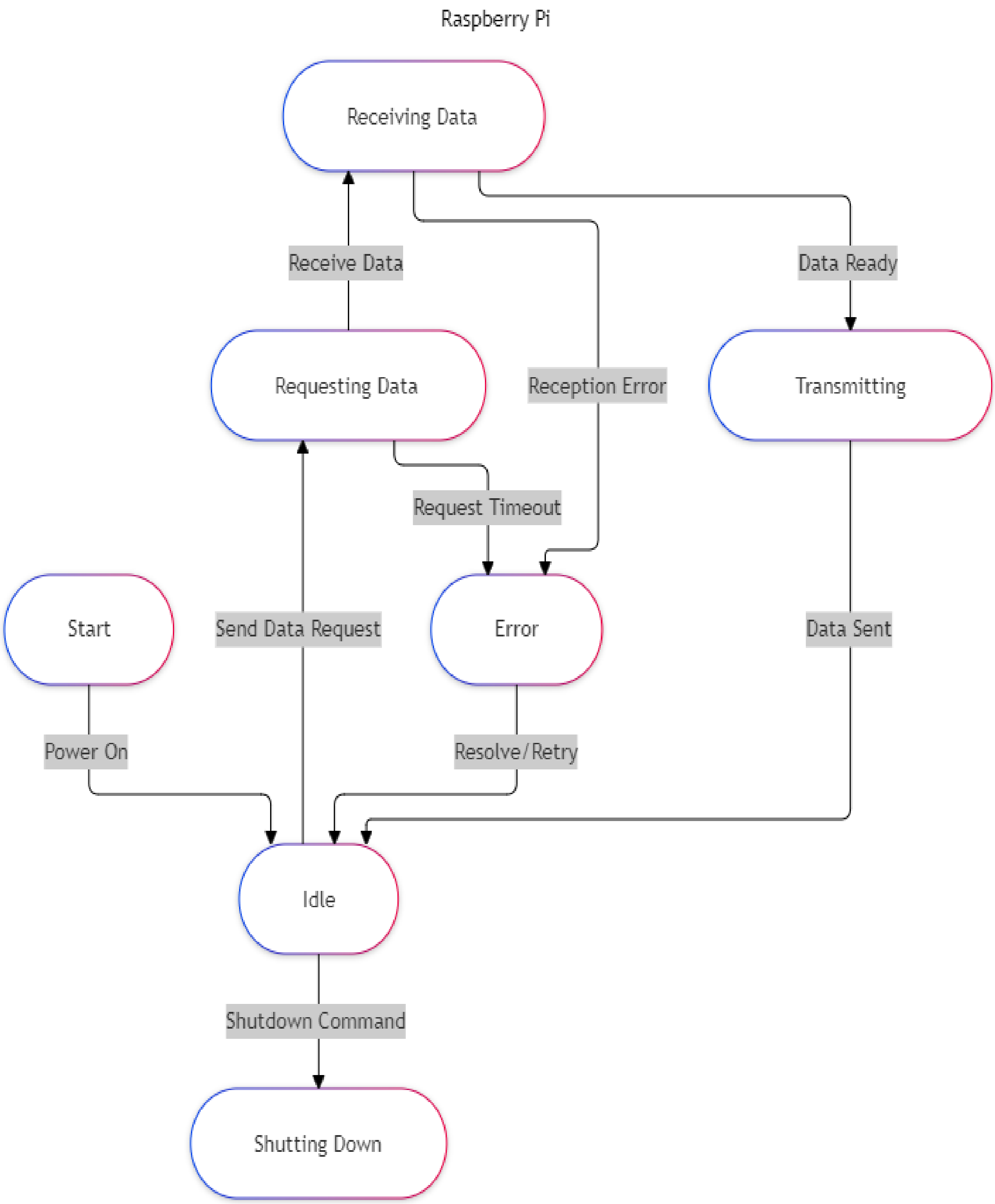

Figure 2.12: State Machine For Raspberry Pi

2.2.10 Sensor Cluster State Machine Diagram

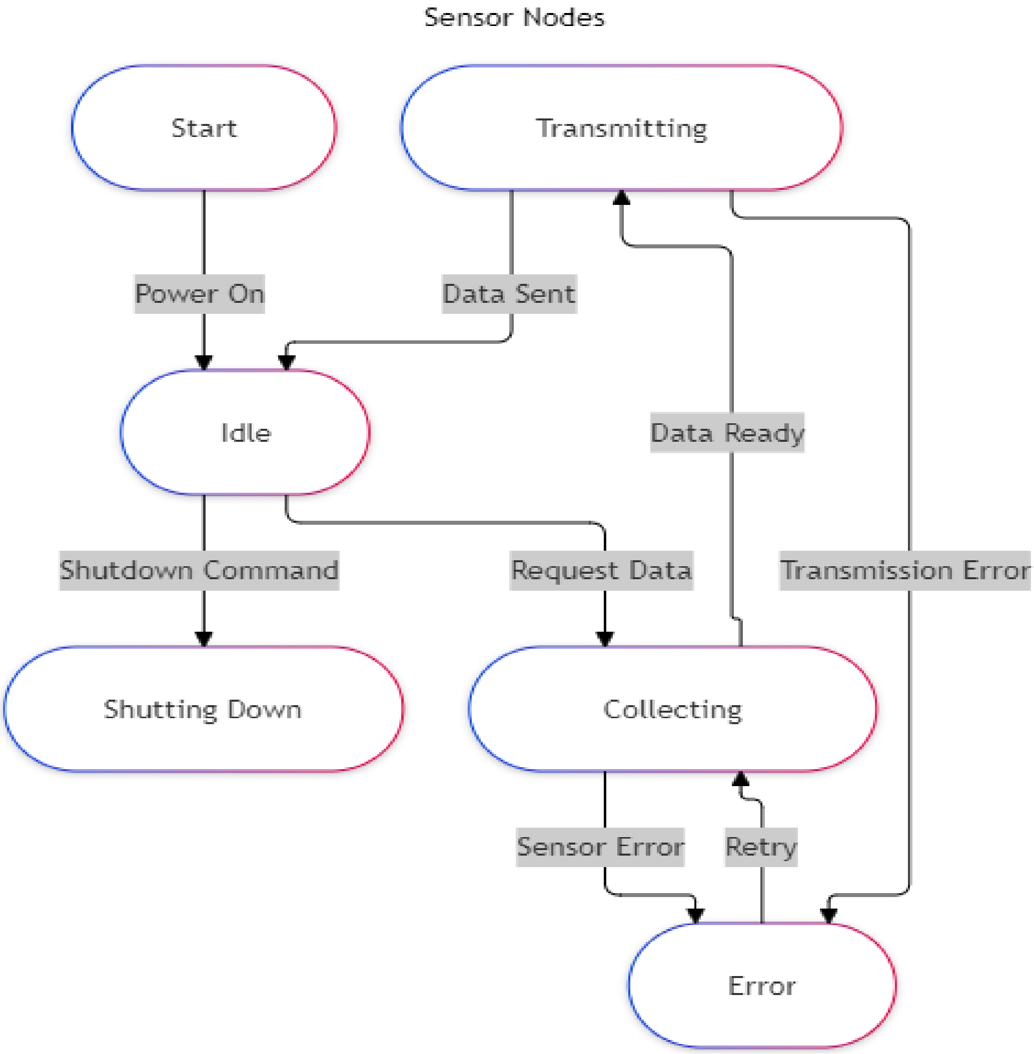

Figure 2.13: State Machine For Sensor Clusters

2.2.11 Server State Machine Diagram

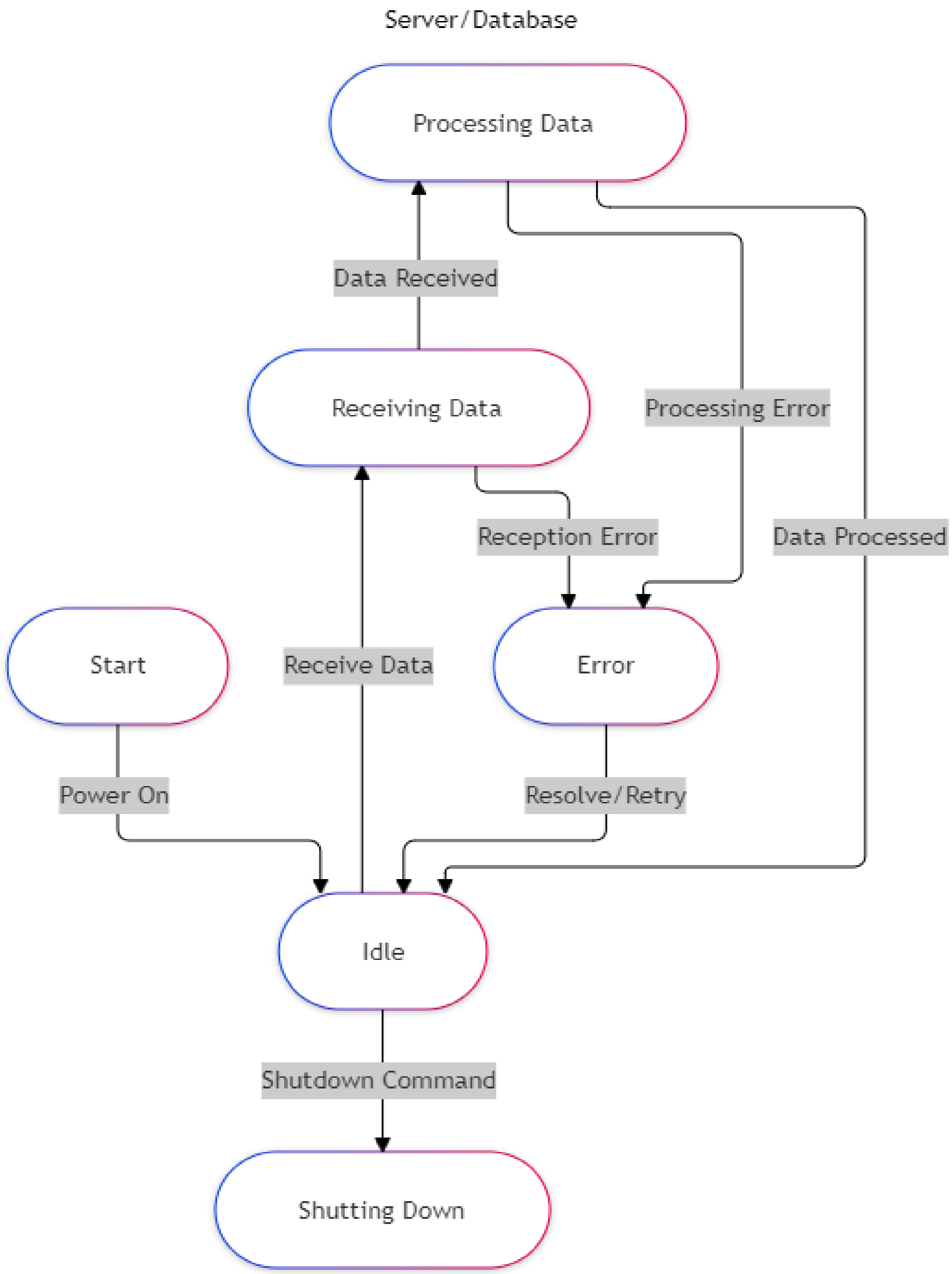

Figure 2.14: State Machine For Server

Website State Machine Diagram

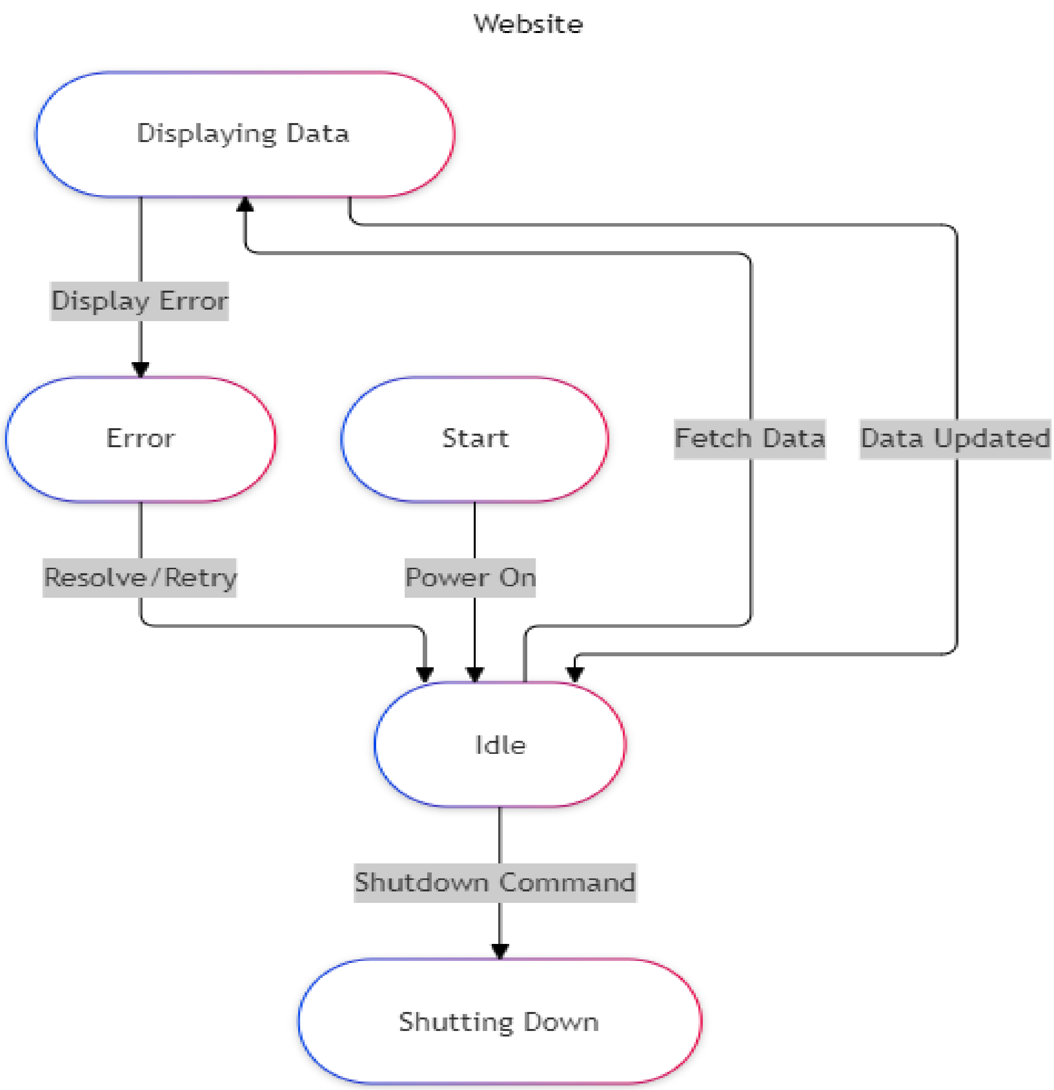

Figure 2.15: State Machine For Website

2.2.12 Component Diagram

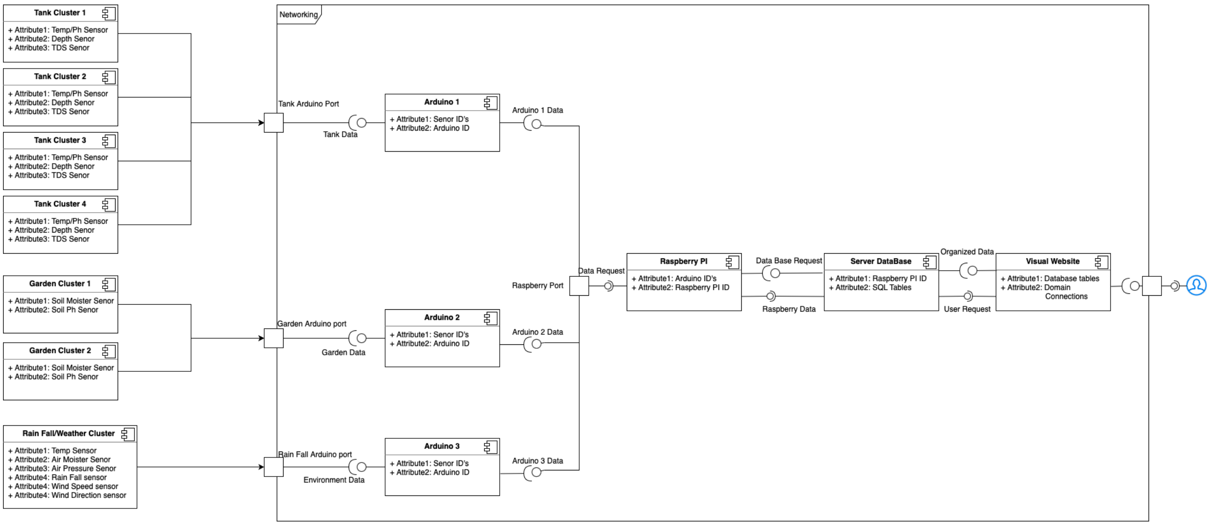

Figure 2.16: Component Diagram

Chapter 3

Software Implementation and Testing

3.1 Test Cases

3.1.1 Arduino Properly transmits Data to Database

Purpose:	
The Purpose of this test case is to ensure that the Arduino can properly transmit data to the database.	
Test Run Information:	
Tester Name:	Prerequisites for Test:
William Kolath	In order for this test to be performed, the gateway, Raspberry Pi hub, and database must be runing.
Date of Test:	Required Configuration:
ENTER DATE	The gateway must be configured to reive data from the Arduino.
Notes:	

TEST SCRIPT STEPS/RESULTS					
Step	Test Step/Input	Expected Results	Actual Results	Requirements Validated	Pass/Fail

Table 3.1: Example Test Case

3.1.2 Example Test Case 2

Purpose:	
Test Run Information:	
Tester Name:	Prerequisites for Test:
William Kolath	Stuff
Date of Test:	Required Configuration:
10/31/24	plug in
Notes:	

TEST SCRIPT STEPS/RESULTS					
Step	Test Step/Input	Expected Results	Actual Results	Requirements Validated	Pass/Fail

Table 3.2: Example Test Case 2

3.1.3 Example Test Case 3

Purpose:	
Test Run Information:	
Tester Name:	Prerequisites for Test:
William Kolath	Stuff
Date of Test:	Required Configuration:
10/31/24	plug in
Notes:	

TEST SCRIPT STEPS/RESULTS					
Step	Test Step/Input	Expected Results	Actual Results	Requirements Validated	Pass/Fail

Table 3.3: Example Test Case 3

3.1.4 Example Test Case 4

Purpose:	
Test Run Information:	
Tester Name:	Prerequisites for Test:
William Kolath	Stuff
Date of Test:	Required Configuration:
10/31/24	plug in
Notes:	

TEST SCRIPT STEPS/RESULTS					
Step	Test Step/Input	Expected Results	Actual Results	Requirements Validated	Pass/Fail

Table 3.4: Example Test Case 4

3.1.5 Example Test Case 5

Purpose:	
Test Run Information:	
Tester Name:	Prerequisites for Test:
William Kolath	Stuff
Date of Test:	Required Configuration:
10/31/24	plug in
Notes:	

TEST SCRIPT STEPS/RESULTS					
Step	Test Step/Input	Expected Results	Actual Results	Requirements Validated	Pass/Fail

Table 3.5: Example Test Case 5

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Appendix A

Backlog

A.1 User Stories for Semester 1

S. No.	Epic / User Stories	Effort	Priority	Sprint	Owner
E1	**Research and Requirements**	**8**	**Very High**	**N/A**	**N/A**
U1.1	Research and List Required Sensors For Data Gathering	2	5	2	Kirk
U1.2	Research Arduino and Required Libraries	2	5	4	Preston, Kirk
U1.3	Research Networking and Connectivity	4	4	4	William, Andre
U1.4	Research Databases and Required Hardware For Server	5	4	3	Preston
U1.5	Research Cameras and Raspberry PI for Image and Video Collection	3	1		
U1.6	Casing landscape For Final/Future Deployment	5	1	3	Kirk
U1.7	Research Server Requirements	3	4	2	Preston
E2	**Hardware Functionality**	**8**	**High**	**N/A**	**N/A**
U2.1	Arduino enclosure and Power	3	3		
U2.3	Raspberry Pi Network Hub Enclosure and Power	2	3		

U2.3	Raspberry Pi Camera Enclosure and Power	2	1	2	William
U2.4	Rain Gauge Functionality	3	4	5	Preston, William
U2.5	Wind Direction Functionality	3	2	5	Preston
U2.6	Wind Speed Functionality	3	2	5	Preston
U2.7	Tank Level Functionality	3	2	5	Hector, Andre, William
U2.8	Water Quality Sensor Functionality	3	4	5	Kirk
U2.8	MKR Shield	3	4	5	Hector
U2.9	LoRaWAN Gateway	3	4	5	William
U2.10	Raspberry Pi Camera Functionality	5	1	2	William
E3	**Server Setup**	**3**	**Mid**	**N/A**	**N/A**
U3.1	Gather and Assemble Server Hardware	3	3	2	Preston
U3.2	Implement and Deploy Sever onto Network	5	4	2	Preston
U3.3	Design a simple Script for Website	2	2	2	Hector
U3.4	Deploy a Simple Website For Data Visualization	5	2		
E4	**Networking**	**5**	**Mid**	**N/A**	**N/A**
U4.1	Hardware Data Transmission to Server	5	3		
U4.2	Server to Internet Communication	3	2		
U4.3	Data Transmission on the Same Network to Server	5	4		
U4.4	Data Transmission Over Distance on Different Networks to The Server	8	5		
U4.5	Peer to Peer Communication Between Sensors and Data Transmission Device	5	2	2	William
U4.6	Cybersecurity for Security From the Unwanted Individuals	8	1		
E5	**Website Functionality**	**2**	**Very Low**	**N/A**	**N/A**
U5.1	Receive Data From Database	4	5	4	Hector

U5.2	Displaying Received Data	2	2		
E6	**Database Design**	**8**	**Mid**	**N/A**	**N/A**
U6.1	Plan Database Structure	5	5	2	Andre
U6.2	Design and Write Database Schema	5	5	3	Andre, Hector, William