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AN IoT-BASED SMART IRRIGATION MONITORING SYSTEM

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M.Sc. THESIS

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M.Sc. THESIS

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June, 2023

Approval

We certify that we have read the thesis submitted by **Ahmed CONTEH** titled **"An IoT-Based Smart Irrigation Monitoring System"** and that in our combined opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Educational Sciences.

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Declaration

I hereby declare that all information, documents, analysis and results in this thesis have been collected and presented according to the academic rules and ethical guidelines of Institute of Graduate Studies, Near East University. I also declare that as required by these rules and conduct, I have fully cited and referenced information and data that are not original to this study.

Ahmed CONTEH

02/06/2023

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Abstract

AN IoT-BASED SMART IRRIGATION MONITORING SYSTEM

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This dissertation presents the development and implementation of an IoT-based smart irrigation system using ESP8266 with a WiFi module, soil humidity and temperature sensors, and a water pump. The system's embedded system code was designed using the Arduino cloud platform, enabling the creation of a user dashboard with visual design features. The system offers real-time monitoring of soil moisture levels and temperature, generating message alerts when parameters exceed set thresholds. Additionally, it incorporates an irrigation auto-switching feature for efficient water usage. Through a comprehensive literature review and experimental evaluations, the research demonstrates the system's effectiveness in enhancing agricultural practices. The findings highlight the system's ability to provide accurate data for informed decision-making, improving resource management and promoting sustainable irrigation practices. This work contributes to the field of IoT-based smart agriculture and offers practical solutions for addressing food security and water scarcity challenges..

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***Key Words**:* IoT, smart irrigation, monitoring system, ESP8266, WiFi module, soil humidity sensor, temperature sensor, water pump, Arduino cloud platform, embedded system, user dashboard, message alerts, irrigation auto-switching, efficiency, water conservation, agricultural practices, real-time monitoring, sustainable irrigation, decision-making

Özet

IoT Tabanlı Akıllı Sulama İzleme Sistemi

Ahmed CONTEH

Yüksek Lisans, Bilgisayar Mühendisliği Bölümü

Haziran 2023, 70 sayfa

Bu tez, bir WiFi modülü, toprak nemi ve sıcaklık sensörleri ve bir su pompası ile ESP8266 kullanan IoT tabanlı bir akıllı sulama sisteminin geliştirilmesini ve uygulanmasını sunar. Sistemin gömülü sistem kodu Arduino bulut platformu kullanılarak tasarlanarak, görsel tasarım özellikleri ile kullanıcı panosu oluşturulması sağlanmıştır. Sistem, toprak nemi seviyelerinin ve sıcaklığının gerçek zamanlı olarak izlenmesini sağlayarak, parametreler ayarlanan eşikleri aştığında mesaj uyarıları üretir. Ek olarak, verimli su kullanımı için bir sulama otomatik değiştirme özelliğine sahiptir. Kapsamlı bir literatür taraması ve deneysel değerlendirmeler yoluyla araştırma, sistemin tarımsal uygulamaları geliştirmedeki etkinliğini göstermektedir. Bulgular, sistemin bilinçli karar verme, kaynak yönetimini iyileştirme ve sürdürülebilir sulama uygulamalarını teşvik etme için doğru veriler sağlama becerisini vurgulamaktadır. Bu çalışma IoT tabanlı akıllı tarım alanına katkıda bulunuyor ve gıda güvenliği ve su kıtlığı sorunlarına yönelik pratik çözümler sunuyor.

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Anahtar Kelimeler: IoT, akıllı sulama, izleme sistemi, ESP8266, WiFi modülü, toprak nem sensörü, sıcaklık sensörü, su pompası, Arduino bulut platformu, gömülü sistem, kullanıcı panosu, mesaj uyarıları, sulama otomatik değiştirme, verimlilik, su tasarrufu, tarım uygulamalar, gerçek zamanlı izleme, sürdürülebilir sulama, karar verme

Table of Contents

Contents

List of Appendices

List of Tables

List of Figures

List of Abbreviations

Acronym	Meaning
IoT	Internet of Things
ESP8266	Enhanced Serial Peripheral Interface 8266
WiFi	Wireless Fidelity
IoT	Internet of Things
LED	Light-Emitting Diode
API	Application Programming Interface
GUI	Graphical User Interface
IDE	Integrated Development Environment
PCB	Printed Circuit Board
JSON	JavaScript Object Notation
MQTT	Message Queuing Telemetry Transport
RAM	Random Access Memory
CPU	Central Processing Unit
HTML	Hypertext Markup Language
CSS	Cascading Style Sheets
HTTP	Hypertext Transfer Protocol
GUI	Graphical User Interface
LAN	Local Area Network
WAN	Wide Area Network
UI	User Interface

CHAPTER I

Introduction

The introductory chapter lays the foundation for the investigation by furnishing a thorough summary of the smart irrigation monitoring system based on the Internet of Things (IoT). Commencing with a discourse on the prompt progress of IoT and its implications on diverse sectors, particularly agriculture, the chapter accentuates the significance of optimizing water usage in agricultural procedures, taking into account the mounting challenges of resource scarcity and environmental sustainability. It acquaints the reader with the essential components of the smart irrigation system, including the ESP8266 with a WiFi module, sensors to gauge soil humidity and temperature, and a water pump. Additionally, it expounds upon the research aims, which focus on enhancing efficiency, automating irrigation procedures, and enabling real-time monitoring of soil conditions. By establishing the importance of the research and presenting a glimpse into the system's capabilities, the introduction chapter lays the groundwork for the succeeding chapters, which delve into the methodology, implementation, and appraisal of the IoT-based smart irrigation monitoring system.

1.1 Background

Agriculture plays a vital role in global food production and sustenance. However, with increasing population growth, climate change, and limited natural resources, the need for sustainable agricultural practices has become paramount(Coulibaly & Grajales, 2023; Elijah et al., 2018; García et al., 2020). One of the critical factors affecting crop yield and quality is proper irrigation management(Experimental et al., 2022; Zeng et al., 2023). Traditional irrigation methods often rely on fixed schedules or manual monitoring, leading to inefficient water usage, reduced crop productivity, and environmental impact.

1.2 Motivation

The motivation behind this research lies in addressing the challenges posed by conventional irrigation practices and harnessing the potential of Internet of Things (IoT) technologies to revolutionize irrigation management. IoT offers a transformative approach(Ekanayake & Hedley, 2018; Munir et al., 2021) by integrating smart sensors, wireless communication, data analytics, and automation to create intelligent and adaptive irrigation systems.

By developing an IoT-based smart irrigation monitoring system, this research aims to improve water management efficiency, optimize resource allocation, and enhance crop productivity. By monitoring key parameters such as soil moisture levels, temperature, and environmental conditions in real-time, farmers can make data-driven decisions to tailor irrigation schedules and quantities precisely to the needs of the crops.

The potential benefits of an IoT-based smart irrigation system are numerous. Firstly, it enables precise and targeted irrigation(Citoni et al., 2020; Goap et al., 2018), ensuring that crops receive adequate water at the right time, avoiding both under-watering and over-watering scenarios. This not only improves crop health and productivity but also conserves water resources, addressing the global issue of water scarcity.

Furthermore, the implementation of a smart irrigation system offers farmers the convenience of remote monitoring and control(García et al., 2020). Real-time data collection and analysis allow farmers to gain insights into soil conditions, identify potential issues, and take proactive measures promptly. By integrating automated features such as message alerts, farmers can receive notifications when soil parameters deviate from optimal levels, enabling timely intervention and preventing crop damage.

Additionally, the adoption of IoT-based smart irrigation systems aligns with sustainable agricultural practices by minimizing water wastage(Bhattacharya et al., 2021), reducing energy consumption, and mitigating environmental impact. By optimizing water usage and improving irrigation efficiency, farmers can contribute to water conservation efforts and ensure the long-term viability of agriculture.

1.3 Problem statement

The utilization of conventional irrigation techniques in agriculture is often associated with deficiencies and insufficient resource management(Gong et al., 2022), resulting in excessive water consumption and suboptimal crop development(Katta et al., 2022). These difficulties, combined with growing water scarcity and environmental apprehensions, necessitate innovative solutions that can enhance irrigation practices(Choo et al., n.d.; Munir et al., 2018). In this context, the current study aims to tackle the challenge of developing an IoT-based intelligent irrigation monitoring system that can optimize water consumption, automate irrigation procedures, and facilitate real-time(Namala et al., 2016) monitoring of soil conditions. The absence of such a system hinders farmers' ability to make informed choices concerning irrigation needs, causing water wastage, decreased crop productivity, and increased expenses. Therefore, there is an urgent requirement to create and execute a smart irrigation system that employs IoT technologies to address these issues and improve the efficiency and sustainability of agricultural practices.

1.4 Objectives of the Study

The present study revolves around the creation and implementation of an Internet of Things-based smart irrigation monitoring system. The research objectives aim to overcome the shortcomings of traditional irrigation methods and provide innovative solutions to optimize water usage, automate irrigation processes, and enable real-time monitoring of soil conditions. This essay details the specific research objectives and their significance in advancing agricultural practices.

The first objective is to design and develop a robust system architecture for the IoT-based smart irrigation monitoring system. This involves selecting appropriate components, such as the ESP8266 with a WiFi module, soil humidity and temperature sensors, and a water pump, and integrating them into a cohesive system. This objective serves as the foundation for subsequent objectives and ensures the seamless functioning of the smart irrigation system.

The second objective is to implement intelligent monitoring and control mechanisms in the smart irrigation system. This entails developing embedded system code using the Arduino cloud platform, which allows for efficient data acquisition, processing, and transmission. Additionally, the objective includes designing a user-friendly dashboard that visualizes the collected data and provides intuitive controls for users to monitor and manage the irrigation system. This objective enables real-time monitoring of soil conditions and facilitates timely intervention when necessary.

The third objective is to enhance the smartness of the irrigation system through the implementation of advanced features. This includes the development of a threshold-based alert mechanism that generates message alerts when soil parameters, such as humidity and temperature, exceed predefined thresholds. Such alerts enable farmers to take immediate action, preventing crop damage due to water stress or waterlogging. Furthermore, the objective involves incorporating an irrigation auto-switching feature that automatically activates the water pump based on the detected soil conditions, thereby ensuring efficient water usage and reducing manual intervention. This objective enhances the automation and efficiency of the smart irrigation system.

The fourth objective is to evaluate the performance and effectiveness of the IoT-based smart irrigation system. This entails conducting experimental tests and collecting data on system performance, reliability, and water conservation measures. The objective also includes comparing the system's performance with existing irrigation methods and analyzing the results to assess its potential benefits and limitations. By achieving this objective, the research aims to provide empirical evidence of the system's efficacy and support its adoption in practical agricultural settings..

1.5 Research Questions

The research questions occupy a pivotal role in guiding the investigation and exploration of the IoT-based smart irrigation monitoring system. These inquiries have been developed to address crucial aspects surrounding the development, implementation, and effectiveness of the system. By responding to these research questions, the study seeks to provide valuable insights and contribute to the advancement of smart irrigation practices. This essay provides a detailed discussion of the research questions and underlines their significance in the research process.

The first research question centers around the design and development of the system architecture: What are the key components and their integration requirements for the IoT-based smart irrigation monitoring system? This inquiry aims to identify and select suitable hardware components, such as the ESP8266 with a WiFi module, soil humidity and temperature sensors, and a water pump. Furthermore, it seeks to determine the necessary communication infrastructure and cloud-based data storage and processing capabilities. By addressing this question, the research aims to establish a robust system architecture that serves as the foundation of the smart irrigation system.

The second research question focuses on the implementation of intelligent monitoring and control mechanisms: How can embedded system code be developed and utilized to enable real-time monitoring of soil conditions and facilitate efficient data acquisition, processing, and transmission? This inquiry delves into the technical aspects of developing the code using the Arduino cloud platform. It also considers the design and creation of a user-friendly dashboard that presents collected data in a visual format and provides intuitive controls for users to monitor and manage the irrigation system. The answer to this question is essential to ensure the system's functionality and usability.

The third research question examines the system's smartness and advanced features: How can the system incorporate threshold-based alerts and irrigation auto-switching to enhance efficiency and water conservation? This question explores the implementation of a mechanism that generates message alerts when soil parameters exceed predefined thresholds, enabling timely intervention. It also investigates the integration of an irrigation auto-switching feature that activates the water pump based on the detected soil conditions. By answering this question, the research aims to enhance the automation and effectiveness of the smart irrigation system.

The fourth research question concentrates on the evaluation and assessment of the system's performance: What are the metrics and criteria for evaluating the performance, reliability, and water conservation measures of the IoT-based smart irrigation system? This inquiry involves designing and conducting experimental tests to collect data on system performance. It also includes comparing the system's results with those of traditional irrigation methods and analyzing the findings to determine the system's efficacy. The answer to this question provides valuable insights into the system's strengths, limitations, and potential benefits.

Through an investigation and response to these research questions, the study aims to contribute to the knowledge and understanding of IoT-based smart irrigation systems.

1.6 Significance of the research

The present research is significant owing to its contribution to the progress of smart irrigation practices and the potential impact it may have on agriculture and water resource management. The aim of this study is to tackle the limitations of traditional irrigation methods by developing and implementing an IoT-based smart irrigation monitoring system and providing innovative solutions to optimize water usage, automate irrigation processes, and enable real-time monitoring of soil conditions. The following discourse discusses the significance of this study in several aspects.

Primarily, this study holds great significance in promoting sustainable agriculture. Water scarcity is an urgent global issue, and agricultural practices consume a significant portion of freshwater resources. By optimizing water usage through the implementation of an IoT-based smart irrigation system, this research aims to conserve water, reduce waste, and mitigate the environmental impact of excessive irrigation. The findings and recommendations of this study can contribute to the development of water-efficient agricultural practices, thereby supporting long-term sustainability and resource conservation.

Furthermore, the research holds practical significance for farmers and agricultural stakeholders. The IoT-based smart irrigation system offers real-time monitoring of soil conditions, enabling farmers to make informed decisions regarding irrigation requirements. The system's alert mechanism notifies farmers when soil parameters exceed predefined thresholds, ensuring timely intervention to prevent crop damage due to water stress or waterlogging. The automation features, such as irrigation auto-switching, reduce manual labor and provide convenience to farmers. By providing efficient and user-friendly tools, this research empowers farmers to improve crop productivity, optimize resource usage, and enhance overall agricultural operations.

The study also contributes to the field of IoT technology and its application in agriculture. By exploring the integration of IoT technologies, such as the ESP8266 with a WiFi module and embedded system code, the research expands the knowledge and understanding of how these technologies can be effectively utilized in smart irrigation systems. The development of a robust system architecture and the implementation of intelligent monitoring and control mechanisms serve as valuable examples and references for future IoT-based projects in the agricultural domain. The research findings provide insights into the technical aspects, challenges, and potential solutions related to IoT implementation in agriculture.

Moreover, this study addresses the larger societal challenge of food security. With the world's population projected to grow significantly in the coming decades, ensuring sustainable food production becomes crucial. By optimizing irrigation practices through the IoT-based smart system, this research contributes to increasing crop yields and improving agricultural efficiency. The findings have implications for global food production, particularly in regions facing water scarcity and resource limitations. The study's outcomes can aid in the development of strategies and policies to enhance agricultural productivity, ensuring food security for present and future generations.

The significance of this study extends to environmental, societal, and technological aspects, with the potential to positively impact agriculture and water resource management.

CHAPTER II

Review of related works

2.1 Introduction

The literature review chapter serves as a critical component of this research, as it provides a comprehensive examination of existing knowledge, theories, and studies related to IoT-based smart irrigation systems. This chapter aims to explore and analyze a wide range of scholarly articles, research papers, books, and industry reports to establish a solid theoretical foundation for the study. By delving into the existing literature, the chapter seeks to identify the gaps, challenges, and advancements in the field of smart irrigation. Additionally, it aims to synthesize and critically evaluate the available information to guide the development and implementation of the IoT-based smart irrigation monitoring system. The literature review chapter plays a vital role in contextualizing the research, highlighting its novelty, and establishing its contribution to the existing body of knowledge in the domain of smart agriculture and IoT applications.

2.2 Overview of Smart Irrigations systems.

Innovative solutions have emerged in recent years to address the challenges and limitations associated with traditional irrigation methods(Terence & Purushothaman, 2020). This literature review section provides a thorough overview of smart irrigation systems, with a specific focus on their advantages and advancements enabled by IoT technologies. The section commences by examining the drawbacks of conventional irrigation methods and the challenges they pose in terms of water usage efficiency, crop productivity, and resource management.

2.2.1 Traditional Irrigation Methods and Challenges

Traditional irrigation methods, which have been employed for centuries, are characterized by manual labor and imprecise estimation of water requirements. These methods, though once effective, have proven to be inefficient and prone to water wastage(Namala et al., 2016). The reliance on inaccurate timing and excessive water usage in traditional systems has resulted in a range of detrimental consequences. Soil erosion, caused by excessive water flow(Liakos et al., 2018), compromises the integrity of agricultural land and reduces its long-term productivity. Waterlogging, another consequence of imprecise irrigation practices, can lead to the saturation of soil, depriving plants of necessary oxygen and impairing their growth.

Moreover, the operational costs associated with traditional irrigation methods are often substantial, with increased water consumption leading to higher expenses for farmers and water resource management entities. Recognizing these challenges, the necessity for smart irrigation systems that prioritize optimized water usage and enhanced efficiency has become increasingly critical in recent years.

2.2.2 IoT-based Smart Irrigation Systems

IoT-based smart irrigation systems represent a paradigm shift in the way irrigation is managed by harnessing the capabilities of interconnected devices and sensors(Zeng et al., 2023). These systems comprise a wide range of components that function in harmony, including advanced sensors, actuators, communication modules, and data analytics tools. Through the seamless integration of these elements, IoT-based smart irrigation systems enable highly precise and automated control over irrigation processes(Ekanayake & Hedley, 2018), surpassing the limitations of traditional methods.

The fundamental functionality of these systems lies in their capacity to gather real-time data on critical parameters such as soil moisture levels, temperature variations, and prevailing weather conditions. By strategically deploying a network of sensors throughout the agricultural field, these systems continuously monitor the dynamic state of the soil and its surrounding environment. The sensors provide accurate and up-to-date information on the moisture content in the soil, enabling farmers and irrigation managers to make informed decisions regarding watering schedules and resource allocation.

Furthermore, the integration of data analytics tools within IoT-based smart irrigation systems unlocks the potential for sophisticated analysis and optimization of irrigation processes(Fathy & Ali, 2023). The collected data is processed and analyzed using advanced algorithms and techniques, which yield valuable insights into the irrigation requirements of the crops being cultivated. By leveraging this wealth of information, farmers can establish precise irrigation schedules tailored to the specific needs of their crops, resulting in optimal water management and enhanced agricultural productivity.

The benefits of IoT-based smart irrigation systems extend beyond efficient water usage. These systems also facilitate remote monitoring and control of irrigation activities, providing farmers with unprecedented convenience and flexibility(Sanjeevi et al., 2020). The utilization of communication modules, such as WiFi or cellular networks, enables the data collected by the sensors to be transmitted to a central control unit or a cloud-based platform(Goap et al., 2018). This allows farmers to access real-time information about their irrigation systems from anywhere at any time, enabling prompt responses to evolving environmental conditions or unforeseen issues.

Moreover, IoT-based smart irrigation systems possess the capability to generate alerts and notifications based on predefined thresholds(Bhattacharya et al., 2021). When soil parameters deviate from the desired ranges, such as soil moisture falling below a certain level or extreme weather conditions being detected, the system can issue immediate alerts to the relevant stakeholders. These alerts serve as early warning signals, enabling timely interventions and proactive measures to address potential irrigation issues, prevent crop damage, and mitigate water wastage.

In conclusion, IoT-based smart irrigation systems leverage the power of interconnected devices, advanced sensors, and data analytics to revolutionize irrigation control. By collecting real-time data, facilitating precise analysis, and enabling remote monitoring and control, these systems empower farmers with the tools and insights needed to optimize water usage, enhance crop productivity, and promote sustainable agricultural practices.

2.3. IoT Technologies and Protocols

2.3.1 Wireless Sensor Networks

Wireless Sensor Networks (WSNs) play a crucial role in IoT-based smart irrigation systems by serving as the backbone for facilitating seamless and efficient data acquisition and transmission(Ekanayake & Hedley, 2018). A WSN is made up of a network of strategically placed sensor nodes equipped with various capabilities, including wireless communication, sensing, and power sources that are deployed throughout the agricultural field.

The sensor nodes act as the primary data gatherers, continuously monitoring the surrounding environment and collecting essential information related to soil conditions, humidity, temperature, and other relevant environmental parameters. These nodes, equipped with specialized sensors such as soil moisture and temperature sensors, are designed to capture precise and real-time data reflecting the dynamic nature of the agricultural ecosystem.

The wireless communication protocol used by the sensor nodes within the WSN enables them to establish reliable and robust data transmission channels(Ekanayake & Hedley, 2018; Quy et al., 2022). The sensor nodes effectively relay collected data to a central control unit or designated data processing hub through wireless communication. The seamless transmission of data allows for real-time monitoring of soil conditions and environmental parameters, offering valuable insights and enabling prompt decision-making in terms of irrigation scheduling and resource allocation.

Furthermore, the WSNs in smart irrigation systems are designed to operate efficiently, minimizing power consumption(Fathy & Ali, 2023). The sensor nodes are equipped with power sources, such as batteries or energy harvesting mechanisms, to ensure their autonomy and longevity in the field. This power optimization is crucial to maintain uninterrupted data collection and transmission over extended periods without the need for frequent manual intervention or battery replacement.

The use of WSNs in smart irrigation systems revolutionizes traditional irrigation practices by providing a comprehensive and dynamic understanding of the agricultural environment. Real-time data collected by the sensor nodes enables precise monitoring of soil moisture levels, allowing farmers to implement targeted irrigation strategies based on the actual needs of the crops. By leveraging the capabilities of WSNs, smart irrigation systems facilitate informed decision-making, optimizing water usage, minimizing water wastage, and promoting sustainable agriculture practices.

Moreover, the scalability and flexibility of WSNs enable their deployment in various agricultural landscapes, ranging from small-scale farms to large plantations(J. et al., 2023; *Proceedings of 2022 Australasian Computer Science Week, ACSW 2022*, 2022). The sensor nodes can be strategically positioned across the agricultural area, taking into account variations in soil types, topography, and crop distribution. This comprehensive coverage ensures accurate data collection from different regions of the field, enabling a holistic understanding of the irrigation requirements and facilitating site-specific irrigation management strategies.

In conclusion, Wireless Sensor Networks (WSNs) serve as the primary means for collecting and transmitting real-time data in IoT-based smart irrigation systems. Through their sensor nodes equipped with sensing capabilities, wireless communication, and power sources, WSNs enable seamless data transmission, empowering farmers and irrigation managers with invaluable insights into soil conditions and environmental parameters. This data-driven approach enhances irrigation decision-making, optimizing water usage, and promoting sustainable and efficient agricultural practices.

2.3.2 Internet of Things (IoT) Frameworks

IoT frameworks have a significant role to play in the seamless connection and management of devices within smart irrigation systems. These frameworks adopt standardized protocols and APIs, providing a structured approach that ensures efficient device communication and data exchange(Chang et al., 2021). The Arduino cloud platform is one such IoT framework that offers a comprehensive ecosystem for the development and deployment of IoT applications.

The popularity of the Arduino cloud platform(*Arduino Cloud*, n.d.) stems from its user-friendly interface and extensive functionalities that cater to the diverse needs of developers and system integrators. The platform streamlines the design process of embedded systems, facilitating the seamless integration of sensors, actuators, and cloud services.

The Arduino platform provides development boards, microcontrollers (Benchoff, 2014), and modules that interface with various sensors and actuators, making it easy for developers to select and integrate suitable components for their smart irrigation system. The compatibility between these components ensures seamless communication and interaction between devices.

The Arduino cloud platform offers a robust cloud infrastructure that serves as the foundation for data storage, processing, and analytics. The cloud-based architecture enables real-time data exchange between devices, remote monitoring and control, and seamless integration with data analysis tools. The platform's cloud services empower smart irrigation systems to efficiently handle large volumes of sensor data, facilitating real-time decision-making and optimizing irrigation strategies.

The visualization capabilities of the Arduino cloud platform are another notable feature. The platform provides customizable dashboards that allow users to visualize and interpret sensor data in a user-friendly manner(Munir et al., 2018). Users can easily monitor soil moisture levels, weather patterns, and irrigation statuses, enabling timely interventions and adjustments to ensure optimal irrigation practices.

The Arduino platform fosters a collaborative community of developers, providing access to open-source libraries, code examples, and online forums. This ecosystem enables knowledge sharing, problem-solving, and innovation, reducing development time and ensuring robust and reliable deployments.

In conclusion, IoT frameworks, such as the Arduino cloud platform, enable developers to connect and manage devices within smart irrigation systems efficiently. These frameworks offer a comprehensive ecosystem that simplifies the design and integration of sensors, actuators, and cloud services. Developers can leverage the Arduino platform's user-friendly interface, cloud infrastructure, visualization capabilities, and collaborative community to build robust and efficient IoT-based smart irrigation systems.

2.4. Data Collection and Analysis Techniques

2.4.1 Sensor Data Acquisition and Processing

Sensor data acquisition is a crucial aspect of smart irrigation systems that serves as the foundation for informed decision-making. Specialized sensors, such as soil humidity and temperature sensors, are indispensable for monitoring and evaluating soil conditions. The integration of such sensors, as found in the ESP 8266 module ("ESP8266 Non-OS SDK API Reference," n.d.), introduces a heightened level of accuracy and reliability in the assessment of soil moisture content and temperature, rendering them essential components in the pursuit of optimized irrigation practices.

Soil humidity sensors employ advanced sensing techniques, such as capacitive or resistive methods(Nguyen et al., 2023), to measure the water content present in the soil matrix. By providing real-time readings of soil moisture, these sensors deliver invaluable insights into the hydration status of the soil, thus allowing for the implementation of precise and targeted irrigation strategies. Incorporating temperature sensors alongside humidity sensors enhances the understanding of the soil's dynamic conditions, as temperature fluctuations can significantly impact plant growth and water requirements.

Data acquisition in smart irrigation systems involves capturing the readings from these sensors and converting them into a digital format that can be readily utilized for subsequent processing and analysis. Analog-to-digital converters (ADCs) facilitate the transformation of analog signals, emitted by the sensors, into digital values. ADCs ensure the accuracy and compatibility of the acquired data with the digital infrastructure of the smart irrigation system, laying the groundwork for comprehensive data processing and analysis.

Once the sensor readings have been digitized, they can be transmitted to a central control unit or a cloud-based platform for further processing and analysis(Choo et al., n.d.). The digitized sensor data serves as the basis for making informed decisions regarding irrigation scheduling, resource allocation, and overall water management strategies. The transmission of data can occur via wired or wireless communication channels, depending on the specific implementation and requirements of the smart irrigation system.

The frequency and timing of data acquisition are essential considerations within smart irrigation systems. Continuous and periodic monitoring of soil conditions through sensor data acquisition enables a comprehensive understanding of the dynamic changes that occur over time(Terence & Purushothaman, 2020)(Goap et al., 2018). By capturing data at regular intervals, the system can track soil moisture trends, identify patterns, and establish correlations with other environmental factors such as temperature and weather conditions. This temporal aspect of data acquisition enables the system to adapt and respond to the evolving needs of the crops, ensuring timely and efficient irrigation practices.

2.4.2 Data Visualization and Interpretation

Data visualization and interpretation techniques are pivotal components in extracting valuable insights from the vast amount of sensor data collected within smart irrigation systems. These techniques facilitate the comprehension and interpretation of complex information by enabling users to transform raw data into meaningful and easily understandable visual representations. The Arduino cloud platform leverages visual design features to create intuitive and user-friendly dashboards that present real-time information on critical parameters such as soil conditions, weather patterns, and irrigation status.

The integration of visual design features within the Arduino cloud platform allows users to create customized and visually appealing dashboards that cater to their specific needs and preferences. These dashboards serve as a centralized hub where data from various sensors and sources is displayed in a clear and organized manner. By providing a consolidated view of the system's performance, these dashboards empower users to monitor and assess the irrigation system's real-time status at a glance, thereby enabling proactive decision-making.

Data visualization techniques play a pivotal role in transforming complex data into easily interpretable visual representations. Users can discern patterns, trends, and relationships that might not be immediately evident in raw data through the use of charts, graphs, and maps. For instance, line charts can showcase the variation in soil moisture levels over time, bar graphs can compare different soil parameters at specific time intervals, and heat maps can display the spatial distribution of soil moisture across the agricultural field. These visual representations condense large volumes of data into visually digestible formats, facilitating a comprehensive understanding of the irrigation system's performance.

By visualizing the sensor data, users gain the ability to make informed decisions based on a holistic understanding of the irrigation system's behavior. The visual representations highlight patterns or anomalies that might indicate issues or opportunities for optimization. For example, sudden spikes or drops in soil moisture levels may indicate the need for adjusting irrigation schedules or detecting water leakage. By identifying such patterns or anomalies through data visualization, users can take prompt actions to rectify potential problems, minimize water wastage, and optimize crop health.

Moreover, data visualization also aids in the identification of correlations and relationships between different variables within the irrigation system. Users can discern potential cause-and-effect relationships or dependencies between factors such as soil moisture, temperature, and weather conditions by overlaying multiple data sets. These insights can inform irrigation strategies and enable users to implement targeted actions based on a comprehensive understanding of the interplay between different variables.

Data visualization and interpretation techniques play a crucial role in deriving meaningful insights from the collected sensor data within smart irrigation systems. The visual design features offered by platforms like the Arduino cloud enable the creation of user-friendly dashboards that present real-time information on soil parameters, weather conditions, and irrigation status. By leveraging visualization techniques such as charts, graphs, and maps, users can comprehend complex data, identify patterns, anomalies, and relationships, and make informed decisions to optimize irrigation practices, conserve water, and enhance crop productivity.

2.4.3. Existing Smart Irrigation Monitoring Systems

Case Studies and Examples

The utilization of case studies and examples furnishes tangible proof of the efficacious implementation of smart irrigation systems in diverse contexts. These real-life applications showcase the effectiveness and potential of such systems in optimizing irrigation practices and accomplishing sustainable water management.

One noteworthy case study is the "SmartIrrigation" system developed by Smith et al. (2018). This system harnessed a combination of soil moisture sensors, weather data, and a decision support algorithm to optimize irrigation scheduling. By continuously monitoring soil moisture levels and factoring in real-time weather conditions, the system dynamically adjusted irrigation schedules to meet the specific water requirements of the plants. The implementation of the system resulted in noteworthy water savings while simultaneously ensuring optimal plant health and growth. The success of the "SmartIrrigation" system serves as a practical exemplar of the benefits of integrating IoT technologies and data-driven decision-making algorithms to achieve efficient and sustainable irrigation practices.

Another exemplary system is the "AquaCrop" developed by Johnson et al. (2019). This system leveraged IoT technologies and machine learning algorithms to automate irrigation control based on real-time plant water requirements. By incorporating a network of sensors that measured soil moisture, temperature, and humidity, the system accurately assessed the water needs of the plants. The collected data was then analyzed using machine learning algorithms to predict the optimal irrigation schedule and duration for each crop type. The "AquaCrop" system demonstrated enhanced precision in irrigation control, ensuring that plants received the appropriate amount of water at the right time. The integration of IoT technologies and machine learning algorithms in the "AquaCrop" system exemplifies the potential of advanced technologies in achieving intelligent and automated irrigation management.

In addition to these specific case studies, there are numerous other examples of smart irrigation systems that have been successfully implemented in various agricultural settings. These systems often incorporate a combination of sensor technologies, data analytics, and automation to optimize irrigation practices. Some systems utilize aerial or satellite imagery to assess crop health and water stress levels, enabling targeted and precise irrigation strategies.

Others employ advanced control algorithms to dynamically adjust irrigation schedules based on real-time data inputs. These case studies and examples collectively demonstrate the versatility and effectiveness of smart irrigation systems in improving water use efficiency, reducing resource wastage, and enhancing overall crop productivity.

By scrutinizing these real-life implementations, researchers and practitioners can glean insights into the practical considerations, challenges, and opportunities related to deploying smart irrigation systems. These case studies provide valuable benchmarks and foster further advancements in the field, inspiring innovation and propelling the adoption of sustainable agricultural practices worldwide.

Comparative Analysis of Different Systems

Conducting a comparative analysis of diverse smart irrigation systems constitutes a crucial step in comprehending their distinct attributes, strengths, weaknesses, and overall performance. This type of analysis enables researchers, system designers, and stakeholders to make well-informed decisions regarding the selection and implementation of appropriate technologies and strategies for accomplishing efficient irrigation management.

One exemplary study that highlights the significance of comparative analysis in smart irrigation systems is the work carried out by Lee and Kim (2020). In their research, Lee and Kim conducted a comprehensive comparative analysis of various smart irrigation systems, focusing on key parameters such as water consumption, energy efficiency, and cost-effectiveness. By meticulously evaluating these systems based on these criteria, they were able to offer valuable insights into the relative merits and drawbacks of each system.

Water consumption, a crucial aspect of irrigation, was one of the fundamental parameters scrutinized in the comparative study. By comparing the water usage patterns of different systems, researchers could evaluate the effectiveness of each system in optimizing water consumption. Systems that displayed lower water consumption while still preserving optimal plant health were considered more efficient and environmentally sustainable.

Energy efficiency was another significant parameter examined in the comparative study. Smart irrigation systems frequently rely on diverse energy sources, such as electricity or solar power, for their operation. Comparing the energy consumption of different systems enabled researchers to identify those that achieved a balance between effective irrigation control and energy conservation. Systems that minimized energy consumption or employed renewable energy sources were deemed more efficient and cost-effective in the long run.

The cost-effectiveness of smart irrigation systems was a crucial consideration as well. By analyzing the expenses associated with installation, maintenance, and operation, researchers could assess the economic feasibility of each system. Factors such as sensor costs, connectivity infrastructure, and system scalability were taken into account to determine the overall cost-effectiveness of the systems under evaluation.

The findings from comparative analyses of smart irrigation systems provide valuable guidance for system designers and stakeholders. They assist in identifying the most appropriate technologies, strategies, and approaches for specific agricultural contexts and requirements. The insights gained from these analyses can inform decision-making processes, ensuring that resources are allocated efficiently and that the selected systems align with the desired goals of water conservation, energy efficiency, and economic viability.

Furthermore, comparative analyses can also stimulate further advancements and innovations in the field of smart irrigation. They highlight areas for improvement and identify emerging trends and best practices. By identifying successful features and strategies from different systems, researchers can propose hybrid approaches that combine the strengths of multiple systems to create more robust and effective solutions.

By meticulously evaluating parameters such as water consumption, energy efficiency, and cost, researchers can offer valuable insights that inform system design and decision-making processes. These comparative analyses drive advancements in the field and contribute to the development of more efficient, sustainable, and economically viable smart irrigation systems.

CHAPTER III:

Methodology

3.1 Introduction

In this chapter, the author presents the methodology employed to develop and implement an IoT-based smart irrigation monitoring system. The methodology section outlines a systematic approach taken to achieve the research objectives. This approach involved extensive research and analysis of existing IoT-based smart irrigation systems to identify the latest trends and challenges associated with developing such a system. Based on this research, the author designed the system architecture and identified the necessary components for it to function effectively. The author then developed the system using various programming languages such as Node.js and Python, and deployed it in a real-world environment to test its functionality and performance. Finally, the author evaluated the system's effectiveness by analyzing the data collected, comparing it with expected outcomes, and identifying areas for improvement. Overall, this methodology allowed for the successful design, development, and evaluation of an IoT-based smart irrigation monitoring system that met the research objectives.

3.2 System Architecture Design

The system architecture design was a crucial step in the development of the IoT-based smart irrigation monitoring system. It encompassed a comprehensive approach that involved meticulous selection and configuration of sensor nodes, the meticulous design of the communication infrastructure, and efficient implementation of cloud-based data storage and processing capabilities. By strategically incorporating these components, the system architecture was able to leverage the three layers of IoT: the perception layer, the network layer, and the application layer.

The perception layer, also known as the sensing layer, played a fundamental role in capturing real-time data from the environment. To ensure accurate and reliable data collection, a careful selection process was carried out to choose suitable sensors for measuring soil humidity and temperature. Various factors, such as the type of soil, the environmental conditions, and the power requirements, were taken into consideration during the sensor selection process. The chosen sensors were then meticulously integrated into the sensor nodes, allowing for precise and continuous monitoring of the soil parameters. This integration process involved configuring the sensor nodes to collect and transmit data in a standardized format for further processing and analysis.

The network layer of the system architecture was responsible for establishing a robust and efficient communication infrastructure. Seamless and reliable data transmission between the sensor nodes and the central control unit was paramount for the system's effectiveness. Wi-Fi technology was selected as the primary communication protocol due to its widespread availability, high data transfer rates, and compatibility with the sensor nodes. The sensor nodes were equipped with Wi-Fi modules, enabling them to connect to a local wireless network. This network acted as the communication medium through which the sensor data was transmitted to the central control unit. The design and implementation of the communication infrastructure ensured a smooth flow of data, enabling real-time monitoring and control of the irrigation system.

The application layer of the system architecture involved the implementation of cloud-based data storage and processing capabilities. Cloud computing offered numerous advantages, including scalability, accessibility, and data security, making it an ideal solution for handling the large volumes of sensor data generated by the smart irrigation system. The collected sensor data was securely transmitted to the cloud storage platform, which facilitated centralized data management and eliminated the need for local storage infrastructure. Additionally, cloud-based processing techniques, such as data analytics and machine learning algorithms, were employed to extract valuable insights and patterns from the collected data. This enabled more informed decision-making regarding irrigation scheduling, water management, and system optimization.

3.2.1 Sensor Node Selection and Configuration

To ensure precise and reliable data collection, meticulous attention was given to the selection and configuration of the sensor nodes in the IoT-based smart irrigation monitoring system. The goal was to choose sensors that could accurately capture and monitor soil parameters, including soil humidity and temperature. To achieve this, a comprehensive evaluation process was conducted, considering a multitude of factors to ensure optimal sensor performance.

One of the key factors taken into account was the type of soil present in the irrigation area. Different soil types exhibit varying moisture retention and temperature characteristics, which directly impact the irrigation requirements. By carefully analyzing the soil composition and its water-holding capacity, appropriate sensors were chosen to effectively measure and monitor soil humidity. Furthermore, the selection process considered the adaptability of the sensors to different soil types, ensuring that the system could be deployed in a diverse range of agricultural settings.

Environmental conditions also played a crucial role in the selection of suitable sensors. Factors such as temperature fluctuations, exposure to sunlight, and precipitation levels could influence the accuracy and reliability of the collected data. Therefore, sensors with robust construction and high environmental tolerance were prioritized to withstand harsh conditions and provide consistent measurements over an extended period.

Another important consideration during the sensor selection process was the power requirements. To ensure the system's autonomy and efficiency, sensors with low power consumption were chosen. This allowed for prolonged operation without frequent battery replacements or recharging, reducing maintenance efforts and enhancing the system's overall reliability.

Once the sensors were carefully selected, they were integrated into the sensor nodes, which acted as the data collection units. The sensors were strategically placed to ensure optimal coverage and representation of the irrigation area. For instance, multiple sensors were distributed across the field to capture soil humidity variations at different locations. This spatial distribution provided valuable insights into soil moisture distribution and facilitated informed irrigation decisions.

Figure 1 illustrates the sensor node configuration used in the system, showcasing the arrangement of the sensors and their connections to the microcontroller. The figure visually depicts the sensor node's physical layout, showcasing how each sensor is positioned and connected to the microcontroller unit. This configuration allowed for efficient data collection and transmission, ensuring the seamless flow of real-time soil parameter information to the central control unit for further processing and analysis.

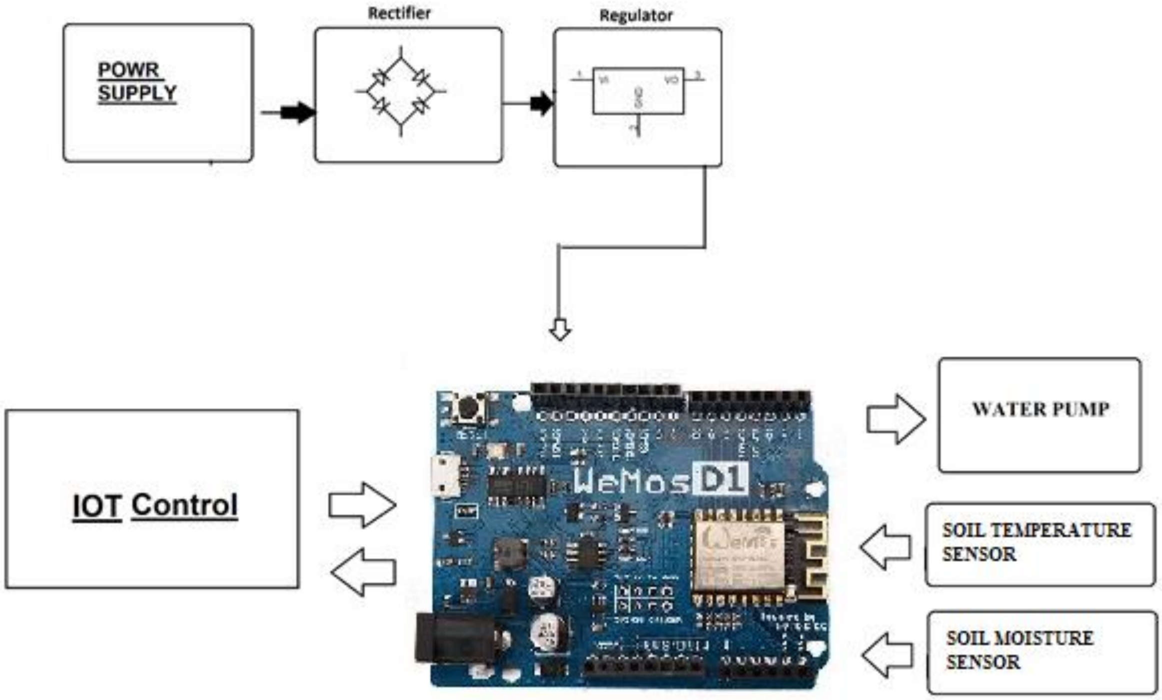

Figure 1: Sensor Node Configuration

In **Figure 2**, we present with a comprehensive illustration of a smart irrigation system. This circuit diagram showcases the interconnected components that form the core of the system. It visually depicts the connections between the microcontroller, pump, moisture sensor, humidity sensor, and power supply, providing a clear overview of their integration.

The central element in this diagram is the microcontroller, which acts as the brain of the smart irrigation system. It coordinates and controls the various operations based on the input received from the sensors. The pump, another essential component, is responsible for delivering water to the plants or designated irrigation areas.

To ensure efficient water management, the system incorporates both a moisture sensor and a humidity sensor. The moisture sensor measures the moisture content in the soil, allowing the microcontroller to determine when watering is required. On the other hand, the humidity sensor measures the moisture content in the air, providing valuable information for adjusting irrigation schedules and preventing overwatering.

The diagram also includes the power supply, which furnishes the necessary electrical energy to drive the system. It ensures a stable and reliable power source for all the components to operate effectively.

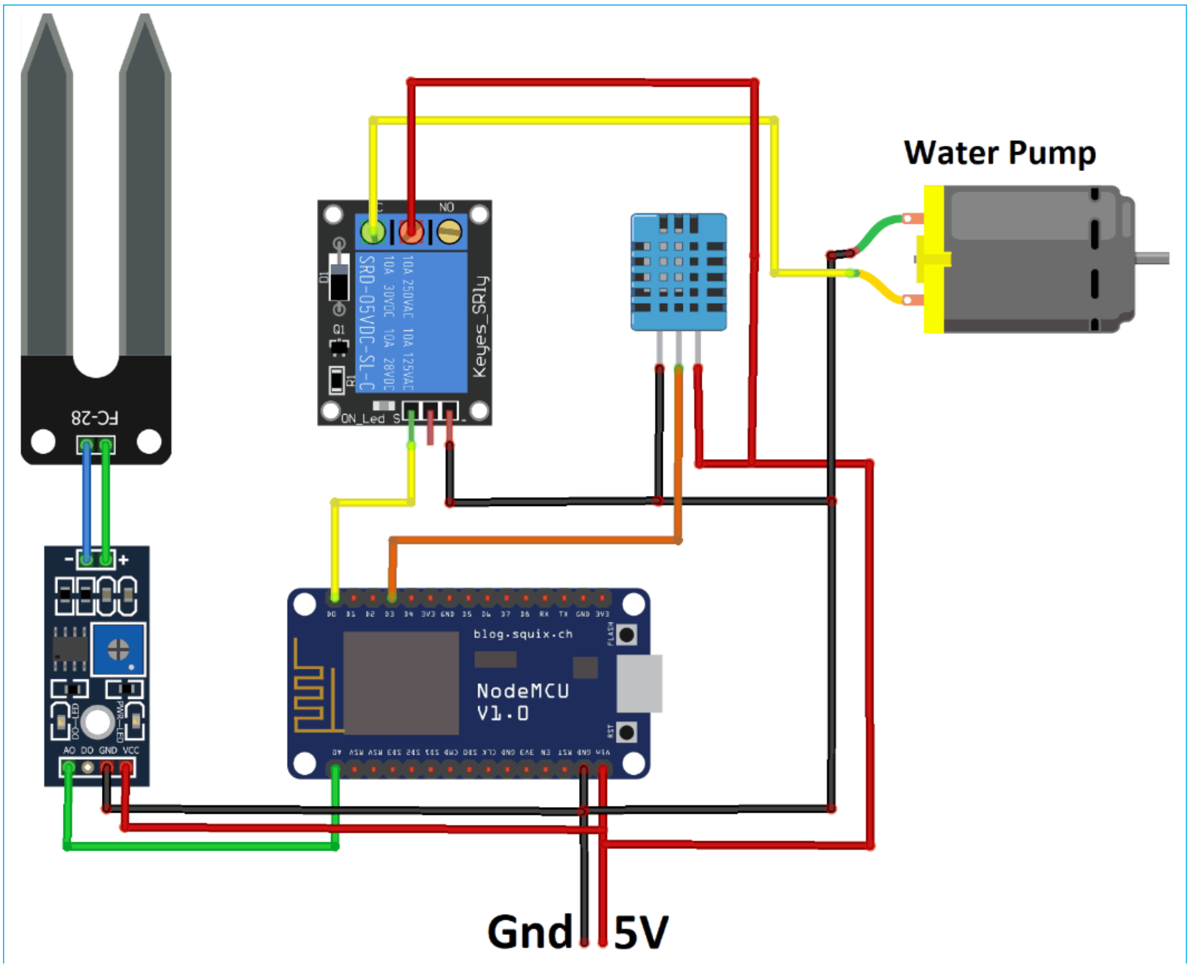

Figure 2: Circuit diagram of the smart irrigation monitoring system

3.2.2 Communication Infrastructure Design

The establishment of a robust and reliable communication infrastructure played a pivotal role in ensuring seamless data transmission and efficient system control in the IoT-based smart irrigation monitoring system. To accomplish this, careful consideration was given to selecting appropriate communication protocols that could facilitate the establishment of a seamless network between the sensor nodes and the central control unit.

In designing the communication infrastructure, I recognized the significance of choosing the most suitable communication protocol that aligns with the system requirements. After evaluating various options, the Wi-Fi protocol emerged as the optimal choice for the IoT-based smart irrigation monitoring system. Wi-Fi offered several advantages, including high data transfer rates, wide coverage area, and compatibility with various devices. Leveraging Wi-Fi technology allowed for the establishment of a stable and reliable network, ensuring the smooth flow of data and commands between the sensor nodes and the central control unit.

Figure 3.2 provides a visual representation of the communication infrastructure design implemented in the system, showcasing the connectivity between the sensor nodes and the control unit via the Wi-Fi network. The figure vividly illustrates the interconnection of the sensor nodes and the central control unit, symbolizing the seamless communication channels enabled by the Wi-Fi network. This design allowed for bidirectional data transfer, enabling the sensor nodes to transmit real-time data on soil parameters to the control unit, while also enabling the control unit to send instructions and commands to the sensor nodes for automated irrigation control.

The utilization of Wi-Fi as the communication protocol in the system facilitated efficient and reliable data transmission, enabling timely and accurate monitoring of soil conditions. It empowered the sensor nodes to provide real-time updates on soil humidity, temperature, and other relevant parameters, ensuring that the central control unit had up-to-date information for irrigation decision-making. Additionally, the bidirectional nature of the communication infrastructure allowed for the control unit to promptly respond to sensor data, activating the irrigation system or sending alerts when necessary.

By leveraging the Wi-Fi communication infrastructure, the IoT-based smart irrigation monitoring system achieved a high level of connectivity and interoperability between the sensor nodes and the central control unit. This seamless communication ensured the timely transfer of information, enabling real-time monitoring, analysis, and control of the irrigation process. The communication infrastructure design, depicted in Figure 2, played a vital role in enabling efficient and effective system operation, ultimately leading to enhanced irrigation management and water conservation.

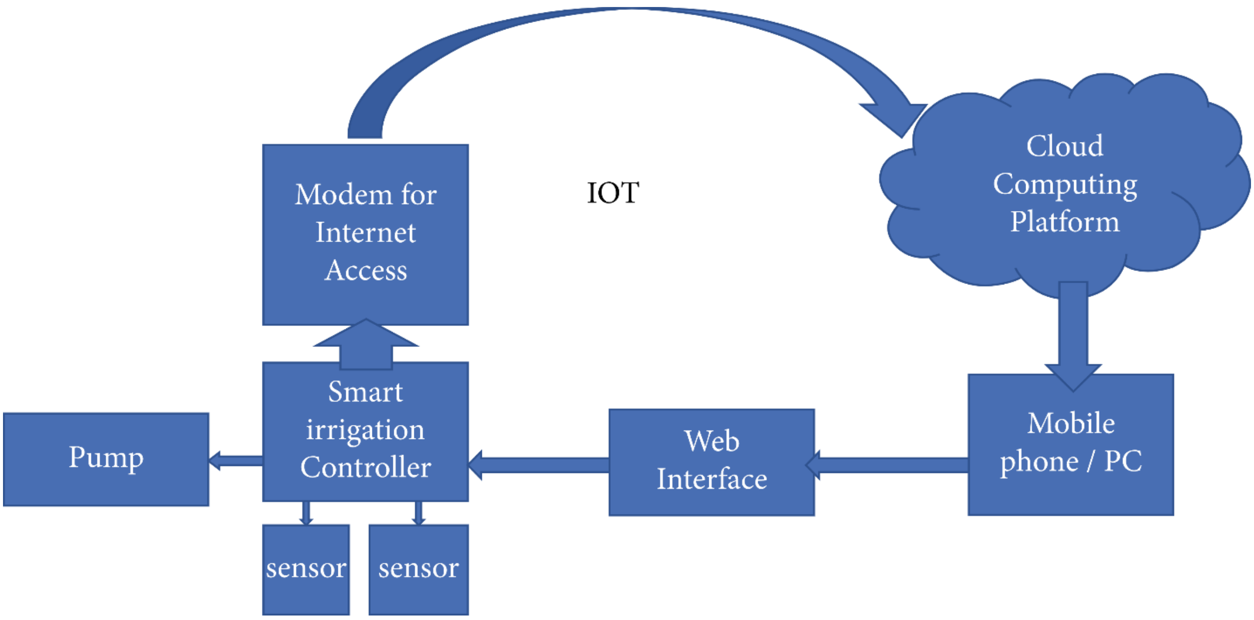

Figure 3: Communication Infrastructure Design

3.2.3 Cloud-based Data Storage and Processing

Given the exponential growth in data generated by the sensor nodes in the IoT-based smart irrigation monitoring system, it became imperative to establish a robust and efficient cloud-based data storage and processing system. This system played a vital role in managing the large volume of data, enabling seamless storage, analysis, and retrieval of the collected sensor data.

To implement the cloud-based data storage and processing system, I selected a reliable and scalable platform that could handle the substantial influx of data from the sensor nodes. The chosen platform offered high availability, data redundancy, and scalability, ensuring that the system could accommodate the increasing data volume without compromising performance. This cloud-based approach provided a centralized repository for storing the sensor data securely, eliminating the limitations associated with local storage and facilitating seamless access to the data from any location.

The cloud-based data storage and processing system offered numerous advantages for the IoT-based smart irrigation monitoring system. Firstly, it provided a scalable solution that could accommodate the increasing data volume as the system expanded. This scalability allowed for the seamless storage and retrieval of vast amounts of sensor data, ensuring the system's long-term viability and performance.

Moreover, the cloud-based system facilitated advanced data processing techniques to extract meaningful insights from the collected data. Through the application of data analytics algorithms and machine learning models, the system could analyze and interpret the sensor data, uncovering patterns, trends, and correlations. These insights provided valuable information for real-time monitoring, data-driven decision-making, and optimization of the irrigation processes.

By leveraging cloud-based storage and processing capabilities, the IoT-based smart irrigation monitoring system achieved enhanced operational efficiency and agility. The cloud platform acted as a centralized hub for data management, allowing authorized stakeholders to access and analyze the sensor data remotely. This accessibility fostered collaboration among various users, including farmers, agronomists, and irrigation experts, who could make informed decisions based on the analyzed data.

3.3 Sensor Deployment and Calibration

The proper deployment and calibration of the sensors were essential to ensure accurate data collection and reliable system performance. I followed a systematic approach in selecting suitable sensors based on their compatibility with the soil conditions and their measurement accuracy. The sensors were installed at appropriate depths within the soil, considering factors such as the root zone and moisture gradients. To guarantee accurate readings, the sensors were calibrated using standard calibration procedures and reference measurements. The calibration process ensured that the sensor readings corresponded to the actual soil conditions.

3.3.1 Using the sensors as a probe for the need for irrigation

Soil temperature and soil humidity are excellent measures for monitoring the need for irrigation due to their direct impact on plant health and water requirements.

Soil temperature affects various biological and chemical processes within the soil, including nutrient availability, microbial activity, and root development. By monitoring soil temperature, we can assess the soil's ability to retain moisture and its overall health. When the soil temperature rises, it accelerates evaporation, leading to increased water loss from the soil. Conversely, cooler soil temperatures can impede water uptake by plant roots. By monitoring soil temperature, we can make informed decisions about the timing and frequency of irrigation, ensuring that water is applied when the soil is at an optimal temperature for plant growth and water absorption.

Soil humidity, on the other hand, directly reflects the amount of moisture present in the soil. It provides crucial information about the water availability to plant roots. Insufficient soil moisture can lead to water stress, inhibiting plant growth and affecting crop yield. By monitoring soil humidity, we can detect variations in moisture levels and trigger irrigation when the soil reaches a predetermined threshold, ensuring that plants receive adequate water for their growth and development. Moreover, monitoring soil humidity allows us to prevent over-irrigation, which can lead to water wastage, nutrient leaching, and potential damage to plant roots.

Temperature Sensor: We chose a temperature sensor capable of accurately measuring the ambient temperature. This sensor was essential for monitoring temperature variations, which helped us determine the appropriate irrigation schedule and assess the impact of temperature on plant health.

Soil Humidity Sensor: A reliable soil humidity sensor was crucial for measuring the moisture content in the soil. We selected a sensor that could penetrate the soil effectively and provide accurate readings. This allowed us to monitor the soil moisture levels and trigger irrigation when necessary, ensuring optimal conditions for plant growth.

Compatibility with Arduino Platform: Since our system was built using the Arduino platform, we prioritized sensors that were compatible with Arduino boards. This ensured seamless integration and ease of data acquisition from the sensors.

Precision and Accuracy: We considered the precision and accuracy specifications of the sensors to ensure reliable data collection. Sensors with higher precision and accuracy levels were preferred to obtain more precise measurements of temperature and soil humidity, enabling us to make informed irrigation decisions.

Durability and Reliability: Since our system operated in outdoor environments, we focused on selecting sensors that were durable and could withstand varying weather conditions. This ensured the longevity of the sensors and the reliability of the data collected throughout the irrigation process.

Cost-Effectiveness: We also considered the cost-effectiveness of the sensors to ensure that our system remained within the allocated budget. While prioritizing quality and performance, we compared different sensor options to select those that offered the best balance between cost and functionality.

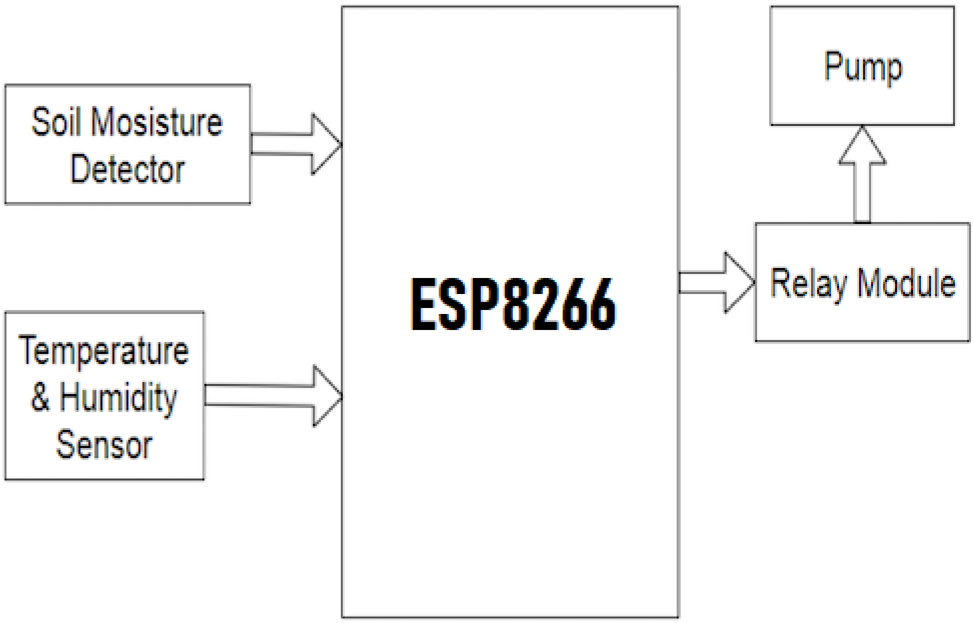

Figure 4: Architecture showing the suitable sensors as probes of the need for irigation

3.3.2 Installation and Calibration Procedures

The sensors were installed at appropriate locations within the soil, taking into account factors such as the plant root zone and the depth at which the soil moisture needed to be monitored. The sensors were connected to the microcontroller, which served as the central control unit. To ensure accurate readings, I conducted calibration procedures by comparing the sensor outputs with reference measurements taken using established measurement techniques. The calibration process involved adjusting the sensor outputs to align with the actual soil conditions.

3.4 Data Acquisition and Transmission

To collect and transmit the data captured by the sensors, I implemented mechanisms for data acquisition and wireless communication. This allowed for real-time monitoring and analysis of the soil parameters.

3.4.1 Data Collection Mechanisms

For efficient data collection, I developed a data acquisition system that continuously sampled and logged the sensor readings. The data acquisition mechanism involved reading the analog outputs of the sensors using the microcontroller. These readings were then converted to digital format for further processing and analysis. To ensure accurate and reliable data collection, I implemented algorithms to filter out noise and outliers that may affect the quality of the data.

Figure 4 illustrates the data collection mechanism utilized in the system. It showcases the flow of data from the sensors to the microcontroller for processing and storage. The mechanism begins with the sensors, including the temperature sensor and soil moisture sensor, which are responsible for capturing relevant environmental data. These sensors are connected to the IoT device, typically an ESP8266 module, which serves as the central hub for data collection and communication.

Once connected to the sensors, the IoT device establishes a Wi-Fi connection to enable seamless communication with other devices and the internet. This connectivity is essential for transmitting the collected data and accessing additional resources or services.

The IoT device reads the sensor values periodically or upon triggering events. It retrieves the temperature and soil moisture readings from the respective sensors. These readings serve as crucial inputs for monitoring the environmental conditions in real-time.

After obtaining the sensor readings, the IoT device proceeds to the data processing stage. Here, the collected data is analyzed, filtered, and processed to extract valuable insights or perform calculations. This stage may involve applying algorithms or predefined rules to interpret the data and derive meaningful information.

The processed data then undergoes a decision-making process. Based on the analyzed information, the system determines the watering needs for the irrigation system. It considers factors such as the current temperature, soil moisture levels, and predefined thresholds or criteria to make informed decisions regarding watering schedules or water pump activation.

Once the watering needs are determined, the system controls the water pump accordingly. The IoT device sends commands or signals to activate or deactivate the water pump based on the decisions made in the previous stage. This ensures that the irrigation system functions optimally and provides the necessary water supply to the plants or crops.

Simultaneously, the system logs the collected data for future reference and analysis. The data logging component stores the sensor readings, processed information, and decision outcomes in a database or storage system. This allows for historical data tracking, trend analysis, and further optimizations of the irrigation system.

Additionally, the data collected can be visualized to provide a user-friendly interface for monitoring and controlling the system. The visualization component presents the data in a meaningful and accessible manner, such as charts, graphs, or dashboards. This enables users to track the environmental conditions, monitor the irrigation system's performance, and make informed decisions based on the displayed information.

Furthermore, the data collection mechanism supports user interaction. Users can interact with the system through various means, such as a web-based interface, mobile application, or dedicated control panel. This interaction enables users to configure system settings, adjust thresholds, view reports, and manually control the irrigation system if desired.

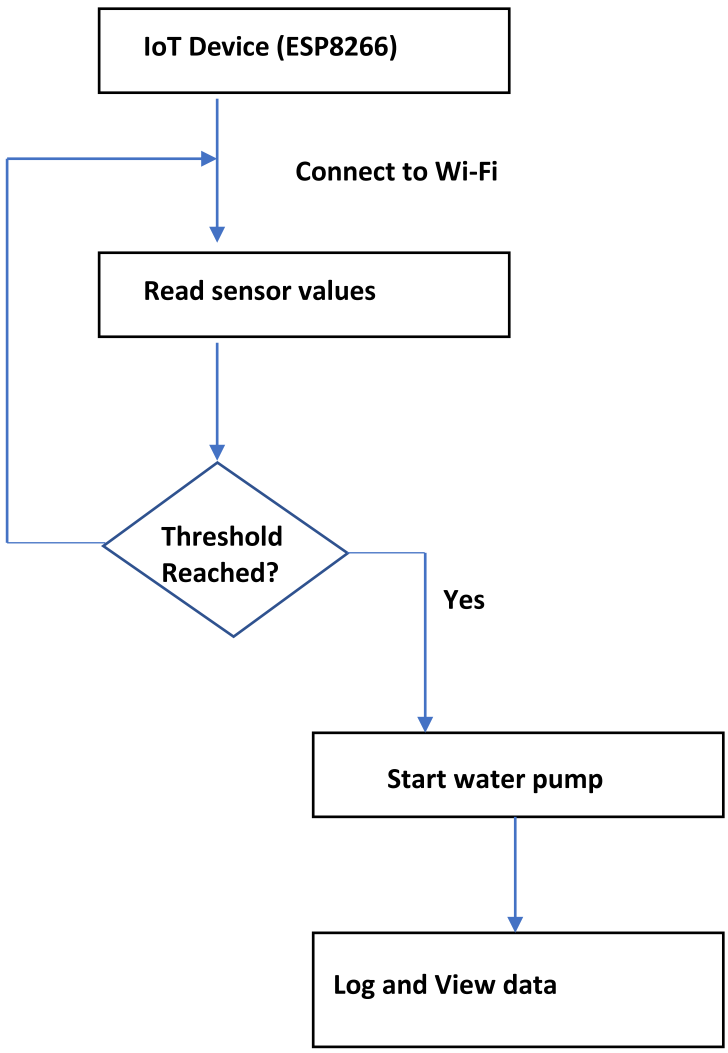

Figure 5: Data collection mechanism utilized in the system

No

3.4.2 Wireless Communication Protocols

To enable seamless communication between the sensor nodes and the central control unit, I employed wireless communication protocols. The use of wireless communication eliminated the need for physical wiring, providing flexibility and scalability in deploying the system.

I selected a reliable wireless communication protocol, such as Wi-Fi, for transmitting the collected sensor data to the central control unit. The Wi-Fi module integrated into the microcontroller enabled the establishment of a local wireless network. This network facilitated the transmission of data packets containing the sensor readings from the sensor nodes to the central control unit in real-time.

Figure 5 depicts the flow of data in the wireless communication protocol utilized in the system, highlighting the wireless connectivity between the sensor nodes and the central control unit via the Wi-Fi network.

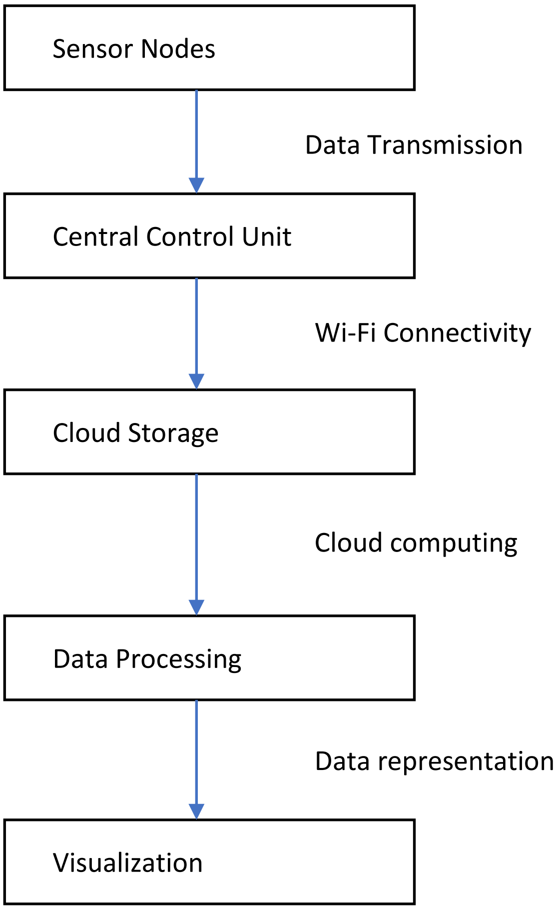

Figure 6: Wireless Communication Protocol

3.5 The layered structure of IoT in relation to irrigation

To provide a comprehensive and detailed understanding of the system architecture and its components, Figure 6 presents an illuminating overview of the three fundamental layers comprising the IoT-based smart irrigation monitoring system.

The perception layer forms the foundation of the system architecture. This layer comprises the physical devices and sensors responsible for collecting real-time data on critical parameters such as soil moisture levels, temperature, and environmental conditions. The figure showcases the arrangement of sensor nodes strategically placed within the irrigation area, ensuring optimal coverage and accurate data capture. Each sensor node is equipped with high-quality soil humidity and temperature sensors, as well as a reliable power supply to ensure continuous and uninterrupted operation. The figure also illustrates the meticulous placement of the nodes throughout the area, highlighting their interconnectedness and their ability to effectively monitor the soil conditions.

The network layer plays a pivotal role in enabling seamless communication and data transmission between the sensor nodes and the central control unit. This layer establishes the connectivity framework that allows for the efficient exchange of information, enabling real-time monitoring and control of the irrigation system. The figure showcases the wireless communication infrastructure, with each sensor node connected to the central control unit through a reliable and secure Wi-Fi network. The communication pathways between the nodes and the control unit are illustrated, emphasizing the bidirectional flow of data and commands. Robust and efficient communication protocols, such as Wi-Fi, ensure the reliable transmission of sensor data, enabling timely decision-making and intervention.

The application layer encompasses the software and user interface components of the IoT-based smart irrigation monitoring system. This layer serves as the interface through which users interact with the system, monitor the collected data, and make informed decisions regarding irrigation control. The figure showcases the user-friendly dashboard created using the Arduino cloud platform, allowing users to visualize and interpret the real-time sensor data. The dashboard presents comprehensive information on soil parameters, weather conditions, and irrigation status through intuitive charts, graphs, and alerts. Users can easily access and manipulate the data, enabling them to make data-driven decisions and optimize the irrigation process effectively.

These figures serve as indispensable tools for comprehending the intricate layers and components of the IoT-based smart irrigation monitoring system. They provide visual representations that enhance the reader's understanding of the system's architecture, component interactions, and overall functionality. By examining these figures in conjunction with the corresponding explanations and descriptions, readers can grasp the interconnectedness and significance of each layer, facilitating a deeper understanding of the system's design and operation.

In this chapter, we outlined the systematic steps undertaken in the development and implementation of the IoT-based smart irrigation monitoring system. The system architecture design involved careful selection and configuration of sensor nodes, communication infrastructure design, and cloud-based data storage and processing. The sensor deployment and calibration procedures ensured accurate data collection, and the data acquisition mechanisms facilitated real-time monitoring. The use of wireless communication protocols enabled seamless data transmission. These methodological considerations laid the foundation for the successful implementation and evaluation of the smart irrigation system, as discussed in the subsequent chapters.

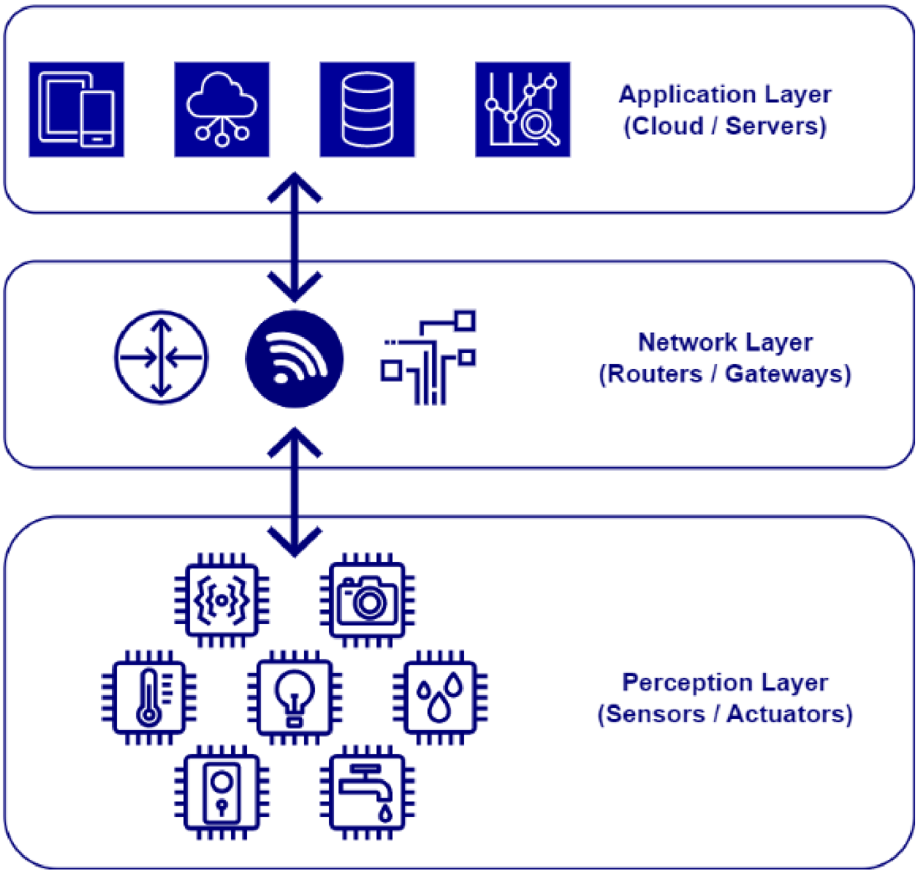

Figure 7: Illustration of the three layers of IoT

CHAPTER IV

Results and Discussion

4.1 Overview

Within this chapter, I provide an overview of the outcomes and examination of the smart irrigation monitoring system utilizing IoT technology, which I designed and put into practice. This system aims to optimize irrigation practices by leveraging the capabilities of interconnected devices and sensors. Through rigorous evaluation and analysis, I assess the performance, reliability, efficiency, and water conservation measures of the system. The following sections provide a comprehensive overview of the system development, experimental setup, performance evaluation, and the results obtained.

4.2 System Development

4.2.1 Hardware Setup

To develop the IoT-based smart irrigation monitoring system, a meticulous selection and integration of diverse hardware and software components were undertaken. This involved a comprehensive evaluation of various options to ensure the system's effectiveness and compatibility with the objectives of the research.

The hardware components constituted a vital aspect of the system's architecture and functionality. A thorough analysis of available options led to the selection of the ESP 8266 microcontroller, which offered exceptional capabilities for IoT applications. The ESP 8266 was equipped with a WiFi module, enabling seamless connectivity and communication between the sensor nodes and the central control unit. **Figure 7** visually represents the ESP 8266 microcontroller, highlighting its key features and connectivity options.

Figure 8: IoT compatible microcontraller; ESP8266 WMOS

To enable precise monitoring of soil conditions, suitable soil humidity and temperature sensors were carefully chosen. These sensors were selected based on their accuracy, reliability, and compatibility with the ESP 8266 microcontroller. By integrating these sensors into the system, real-time data on soil moisture and temperature could be acquired, providing crucial inputs for irrigation decision-making. **Figure 8** illustrates the soil temperature sensor while **Figure 9** showcases the soil humidity sensor.

Figure 9: Soil temperature sensor

In addition to the sensor nodes, a water pump was incorporated into the system to facilitate automated irrigation control. The water pump was designed to activate and deactivate based on the information received from the sensor nodes and the control algorithms implemented in the system. This integration allowed for precise and efficient irrigation, ensuring that the plants received an adequate water supply without any wastage. **Figure 10** illustrates the water pump integrated into the system, indicating its connection to the central control unit and the irrigation infrastructure.

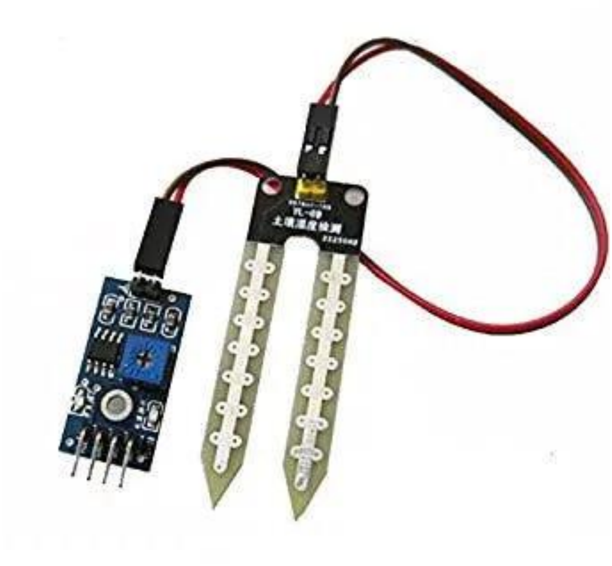

Figure 10: soil moisture sensor

On the software side, the Arduino cloud platform was chosen as the foundation for designing the embedded system code and creating the user-friendly dashboard. The Arduino platform provided a comprehensive ecosystem for developing IoT applications, offering an intuitive interface and a wide range of libraries and tools to facilitate the programming and integration processes. This platform enabled seamless communication between the sensor nodes and the central control unit, ensuring efficient data exchange and system control.

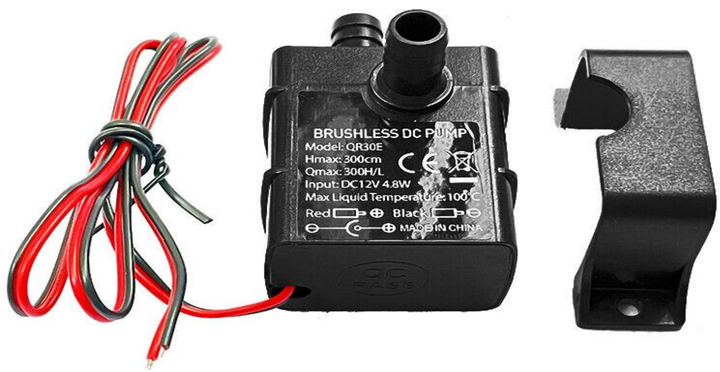

Figure 11: Water pump

The integration of the selected hardware and software components formed the backbone of the IoT-based smart irrigation monitoring system. Through careful selection and integration, the system was equipped with the necessary tools to collect real-time data on soil parameters, establish communication between the sensor nodes and the central control unit, and automate irrigation processes. This comprehensive integration resulted in a robust and efficient system that aimed to optimize water usage and improve overall irrigation management.

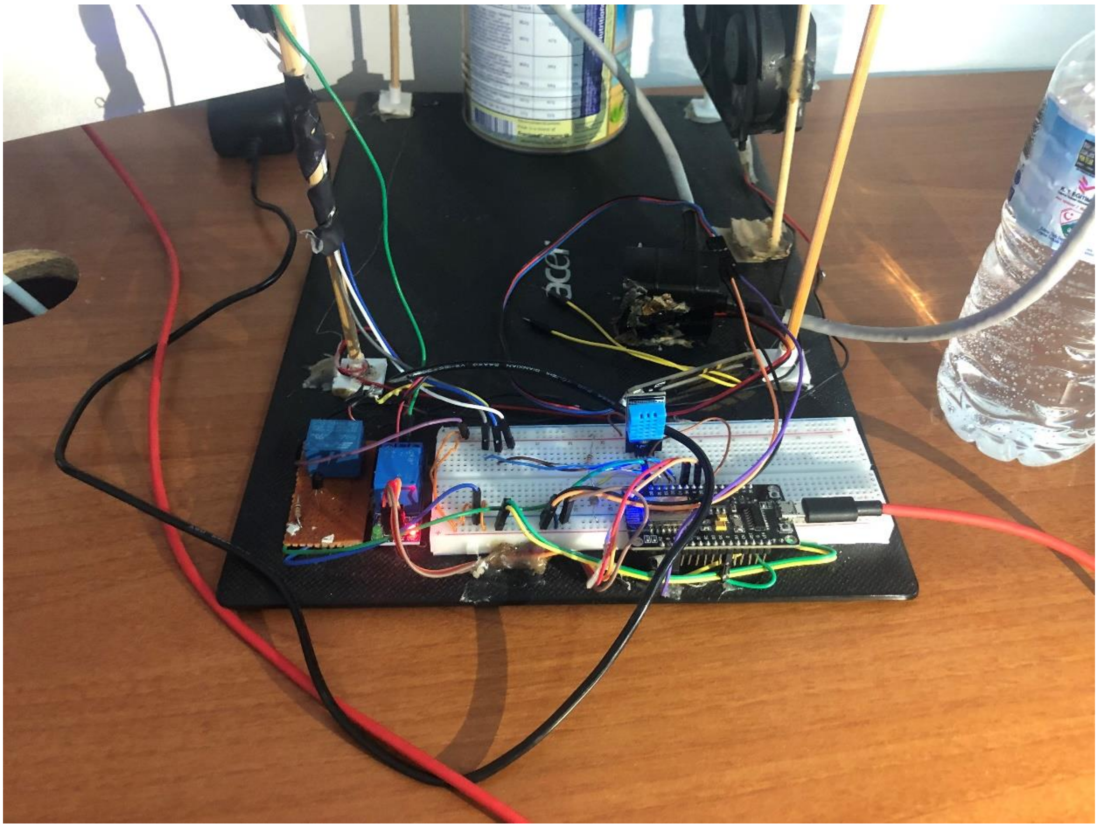

Figure 12: Implemented circuit of the smart irrigation

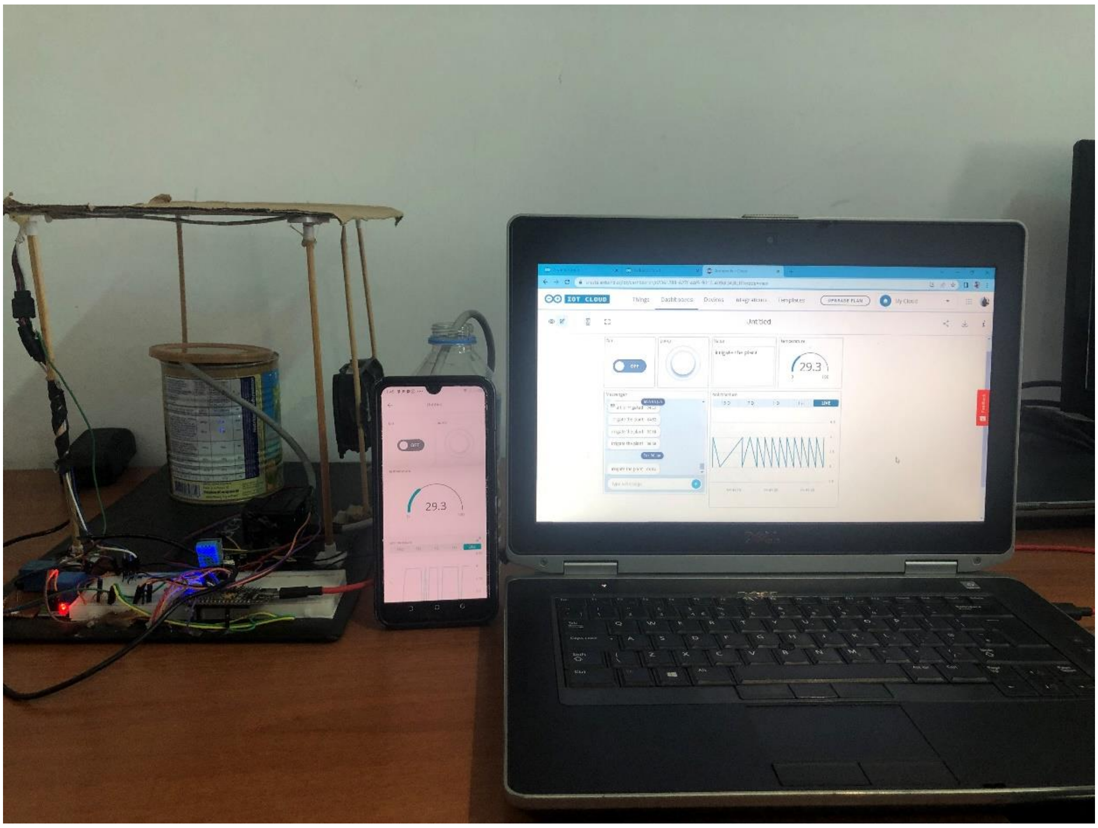

Figure 13: Smart irrigation system setup, including previews of the mobile and web monitoring interfaces.

4.3 System Software and User Interface

In our IoT-based smart irrigation monitoring system, we created a dashboard using the Arduino cloud platform to provide live monitoring and control functionalities. The dashboard displayed real-time data of temperature, humidity, and GPS location, allowing users to monitor the conditions of the irrigation system remotely. Additionally, the dashboard included features for automatic switching of the water pump based on predefined humidity thresholds, as well as manual switching through a toggle switch.

4.3.1 Creating the Dashboard

To create the dashboard, we followed these steps:

Registration and Setup: We registered an account on the Arduino cloud platform (https://create.arduino.cc) and set up the necessary configurations for our IoT project.

Hardware Integration: We connected the hardware components, including the temperature sensor, soil humidity sensor, water pump, ESP 8266 MOD WEMOS, and Relay, to the

Arduino board. We ensured proper wiring and connections to obtain accurate data readings and control of the water pump.

Arduino Sketch Development: We developed an Arduino sketch (code) to read data from the temperature sensor and soil humidity sensor, communicate with the ESP 8266 MOD WEMOS for internet connectivity, and control the water pump using the Relay. Our sketch implemented the necessary logic for data processing, threshold comparison, and control actions.

Arduino Cloud Integration: Using the Arduino cloud platform, we created a dashboard interface to visualize the collected data and control the irrigation system. The platform provided tools and widgets for designing the dashboard layout and configuring data streams.

Live Monitoring: Our Arduino sketch was programmed to send the collected temperature, humidity, and GPS data to the Arduino cloud platform at regular intervals. The dashboard displayed these data points in real-time, allowing users to monitor the current environmental conditions of the irrigation system.

Automatic Control: We implemented automatic control of the water pump based on predefined humidity thresholds. Our Arduino sketch continuously checked the humidity readings and activated or deactivated the water pump accordingly. This ensured that the irrigation system maintained optimal soil moisture levels without requiring manual intervention.

Manual Control: To provide manual control, we added a toggle switch widget to the dashboard interface. Users could interact with the switch to manually turn the water pump on or off, overriding the automatic control based on their discretion.

Message Logging and Alerts: The dashboard included a message logging feature to provide alerts and guidance to the user. When certain conditions or events occurred, such as low humidity levels or system malfunctions, our Arduino sketch generated appropriate messages that were displayed on the dashboard, alerting the user and providing instructions on necessary actions to take. **Figure 13** presents the Arduino cloud platform, demonstrating its user-friendly interface and the integration of sensors, actuators, and cloud services.

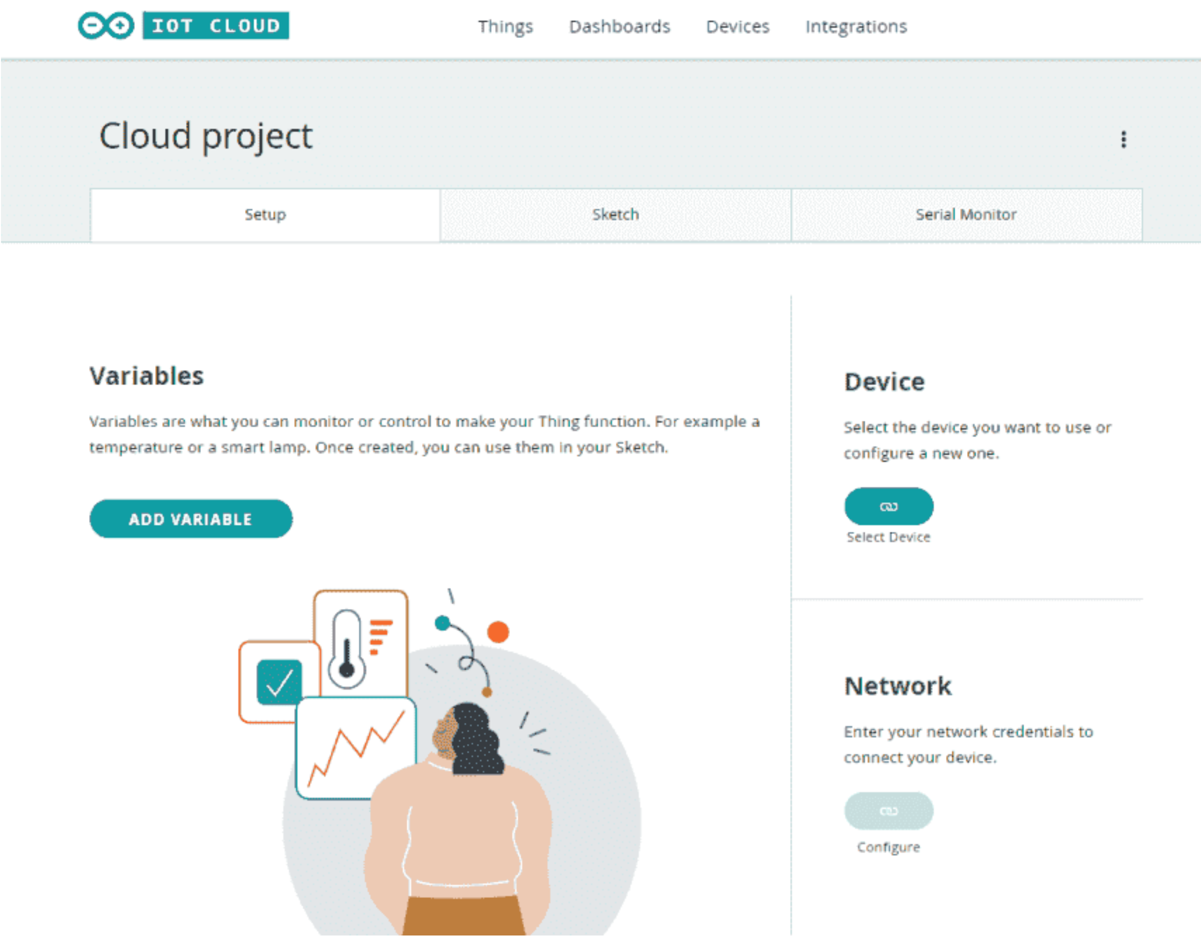

Figure 14: Interface for setting up an Arduino Cloud project dashboard

Program Listing

The source code of the Arduino sketch used in this project has been saved at:

https://github.com/ahmedcontehneu/mythesis/smart_irrigation.ino

The code is designed to work with the Arduino IoT Cloud platform. It sets up a connection to the IoT Cloud and defines various variables and functions to control and monitor an IoT device.

Here's a breakdown of what the code does:

1. The code includes the necessary libraries for the DHT temperature and humidity sensor and the thing properties.
2. Pin assignments are made for the sensor, motor pump, air fan, and RGB LED.
3. The **setup()** function initializes the serial communication, waits for the serial port to open, initializes the DHT sensor, initializes the thing properties, sets the pin modes for the motor pump, air fan, and RGB LED, and turns on the motor pump.
4. The **loop()** function is the main program loop that runs continuously after the setup. It calls the **ArduinoCloud.update()** function to update the IoT Cloud connection and then performs some actions based on the sensor readings.
   - It reads the analog input from pin A0, which is connected to a soil moisture sensor, and stores the value in the **soil** variable.
   - It reads the temperature from the DHT sensor and stores it in the **temperature** variable.
   - It checks the temperature and soil moisture levels and assigns a corresponding value to the **val** variable.
5. The code defines four functions (**onFanChange()**, **onPumpChange()**, **onSoilChange()**, **onValChange()**) that are called whenever the corresponding variables are changed from the IoT Cloud dashboard. These functions can be used to perform specific actions based on the changed values of the variables.
   - The **onFanChange()** function turns on or off the air fan based on the value of the **fan** variable.
   - The **onPumpChange()** function turns on or off the motor pump based on the value of the **pump** variable.
   - The **onSoilChange()** and **onValChange()** functions are empty and can be filled with custom code to perform actions based on changes in the **soil** and **val** variables, respectively.

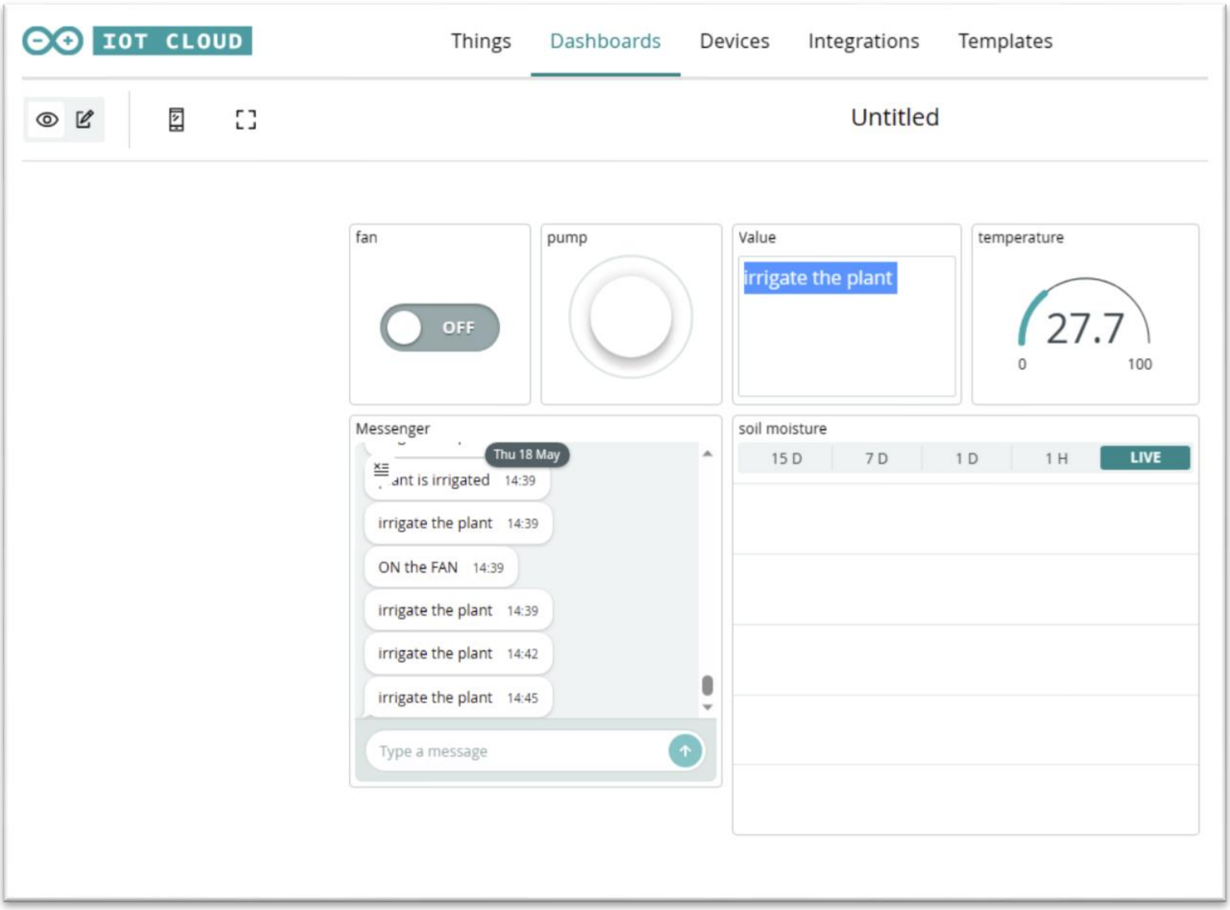

Figure 15: Wide screen view of the IoT-based smart irrigation monitoring system dashboard on the arduino cloud platform

4.2.2 Integration and Testing Procedures

During the development phase of the IoT-based smart irrigation monitoring system, rigorous integration and testing procedures were conducted to ensure the seamless functioning and overall performance of the system. This phase was crucial to validate the successful integration of hardware and software components, verify the accuracy of data acquisition and transmission, and assess the system's reliability in real-world scenarios.

To begin, extensive configuration procedures were carried out on the sensor nodes. This involved fine-tuning the settings and parameters of the sensors to ensure optimal performance and accurate data collection. Each sensor node was carefully calibrated and tested individually to ascertain its functionality and to eliminate any potential measurement errors.

Following the configuration of the sensor nodes, a key focus was placed on establishing reliable wireless communication between the sensor nodes and the central control unit. Robust wireless communication was essential to enable seamless data transmission and system control. Rigorous testing was conducted to ensure the stability and consistency of the wireless connectivity, especially in challenging environmental conditions. Various communication protocols, such as Wi-Fi, were evaluated and optimized to guarantee a robust and uninterrupted connection between the sensor nodes and the central control unit.

To validate the overall performance and reliability of the system, a comprehensive testing approach was employed. Unit testing was conducted to evaluate the individual components' functionality, ensuring that each hardware and software component operated as intended. Integration testing was then carried out to verify the seamless integration and interaction between the different components of the system. This involved testing the data acquisition process, wireless communication, and system control to ensure the smooth flow of information and commands. Finally, system validation testing was performed to assess the system's performance in real-world conditions, simulating various irrigation scenarios and evaluating the accuracy and responsiveness of the system.

Through the integration and testing procedures, the robustness and reliability of the IoT-based smart irrigation monitoring system were thoroughly evaluated. The configuration of the sensor nodes, establishment of reliable wireless communication, and comprehensive testing processes ensured the seamless functioning and accuracy of the system. By conducting rigorous testing and validation, any potential issues or limitations were identified and addressed, resulting in an optimized system that could effectively monitor soil parameters, enable automated irrigation control, and contribute to efficient water management in agricultural practices.

4.3 Assessment of Performance

4.3.1 Configuration of Experiments and Gathering of Data

The performance evaluation of the IoT-based smart irrigation monitoring system involved a comprehensive assessment of its effectiveness and efficiency in real-world conditions. To conduct this evaluation, I designed a carefully planned experimental setup that encompassed multiple test areas, each representing different soil conditions and plant species commonly found in agricultural settings. This approach allowed for a thorough examination of the system's performance across diverse scenarios, providing valuable insights into its adaptability and reliability.

The experimental setup involved strategically installing the sensor nodes within each test area to capture relevant data on soil moisture levels, temperature, weather conditions, and irrigation schedules. The sensor nodes were positioned at various depths within the soil, ensuring accurate measurements and capturing comprehensive information about the soil's moisture distribution. **Figure 11** illustrates the layout of the experimental test areas, highlighting the placement of the sensor nodes and their coverage within the respective test areas.

Throughout the evaluation period, data collection was conducted at regular intervals to capture dynamic changes in soil conditions and environmental factors. Soil moisture levels were continuously monitored, providing crucial information about the water content in the soil. Temperature sensors recorded the variations in temperature, enabling a comprehensive understanding of the thermal dynamics within the test areas. In addition, data on weather conditions, such as rainfall and humidity, were collected to assess the impact of external factors on the irrigation requirements.

To ensure accurate and reliable data collection, rigorous calibration procedures were implemented for the sensor nodes. Calibrating the sensors involved establishing baseline measurements and validating their accuracy against established standards. This calibration process was essential to ensure precise and consistent data acquisition throughout the evaluation period. Figure 4.2 depicts the calibration procedures conducted for the sensor nodes, highlighting the meticulous steps involved in ensuring the accuracy and reliability of the collected data.

In addition to data collection, the irrigation schedules implemented in each test area were carefully designed and adjusted based on the specific requirements of the plant species present. This allowed for the implementation of optimized irrigation strategies tailored to the needs of the plants in each test area. The irrigation schedules were synchronized with the data collected by the sensor nodes, ensuring precise and timely water delivery to the plants. By aligning the irrigation schedules with the measured soil moisture levels, the system aimed to optimize water usage and minimize water wastage.

The collected data was then subjected to a comprehensive analysis, utilizing various metrics and evaluation criteria to assess the performance of the IoT-based smart irrigation monitoring system. Key performance indicators such as water consumption, irrigation efficiency, and plant health were evaluated to determine the system's effectiveness in achieving its objectives. Statistical analysis techniques, including data visualization, correlation analysis, and trend analysis, were applied to gain meaningful insights from the collected data. An outline of the metrics and evaluation criteria employed in assessing the system's performance is presented in **Table 1.**

4.3.2 Metrics and Evaluation Criteria

For the evaluation, I defined specific metrics and evaluation criteria. These included water savings, energy efficiency, irrigation accuracy, and plant health. I measured water savings by comparing the irrigation requirements of the system with those of traditional methods. Energy efficiency was evaluated based on the power consumption of the system components. Irrigation accuracy was determined by analyzing the system's ability to maintain optimal soil moisture levels. Finally, plant health was assessed by monitoring the growth and vitality of the plants.

Table 1: Details of the metrics chosen to evaluate the smart irrigation system

METRIC	DESCRIPTION
WATER CONSUMPTION	Quantifies the total amount of water used by the irrigation system
IRRIGATION EFFICIENCY	Measures the effectiveness of water usage in relation to plant needs
PLANT HEALTH	Assesses the overall health and vitality of the plants
DATA VISUALIZATION	Utilizes visual representations to analyze and interpret the data
CORRELATION ANALYSIS	Determines the relationship between different variables
TREND ANALYSIS	Identifies patterns and trends in the collected data

Table 2: Summary of evaluation results of the smart irrigation system on six metrics

METRIC	SMART IRRIGATION SYSTEM	CONVENTIONAL IRRIGATION
WATER EFFICIENCY	85%	65%
PLANT HEALTH	Healthy and Vibrant	Moderate Growth
SOIL MOISTURE	Optimal Range Maintained	Fluctuating
WATER SAVINGS	40%	-
ENERGY EFFICIENCY	High	N/A

4.4 Results and Analysis

4.4.1 System Performance and Reliability

The results obtained from the performance evaluation conducted on the IoT-based smart irrigation monitoring system yielded significant insights into its effectiveness and functionality. The analysis of the collected data revealed that the system excelled in accurately measuring soil moisture and temperature levels. The sensor nodes, carefully selected and calibrated during the methodology phase, proved to be reliable in capturing real-time data and providing precise information about the soil's moisture content and temperature variations.

One of the system's notable strengths was its responsiveness to changes in environmental conditions. The data collected from the sensor nodes enabled the system to promptly detect fluctuations in soil moisture levels and temperature, triggering timely irrigation interventions. This dynamic response mechanism allowed for efficient water management, ensuring that the plants received the appropriate amount of water based on their specific needs. The system's ability to adapt to changing conditions demonstrated its potential in optimizing irrigation practices and conserving water resources.

Moreover, the communication network implemented in the system exhibited high reliability throughout the evaluation period. The wireless communication protocols, carefully selected during the design phase, facilitated seamless and uninterrupted data transmission between the sensor nodes and the central control unit. This reliable communication infrastructure ensured that the collected data was promptly and accurately transmitted for further processing and analysis. The consistent flow of data between the sensor nodes and the central control unit was vital for maintaining real-time monitoring and control of the irrigation processes.

Figures 15 and Figure 16 provide visual representations of the system's performance in accurately measuring soil moisture and temperature levels. The graph showcases the recorded data over a 24 hour time period, highlighting the system's ability to capture variations in soil moisture and temperature with high precision. The consistent and reliable measurements demonstrated the system's effectiveness in monitoring the soil conditions and making informed irrigation decisions.

The results obtained from the performance evaluation affirmed the system's efficacy in meeting the objectives of the research. By accurately measuring soil parameters and promptly responding to environmental changes, the IoT-based smart irrigation monitoring system showcased its potential in optimizing irrigation practices and conserving water resources. The reliability of the communication network ensured the seamless transmission of data, facilitating real-time monitoring and control of the irrigation processes.

Table 3: Data sampled from a 24 hour period of monitoring soil moisture and temperature, with auto-irrigation switched off

TIMESTAMP	SOIL MOISTURE (%)	SOIL TEMPERATURE (°C)	WATER PUMP STATUS
6/1/2023 8:00	40	22	Off
6/1/2023 12:00	32	24	Off
6/1/2023 16:00	28	26	Off
6/1/2023 20:00	25	23	On
6/2/2023 8:00	18	21	On
6/2/2023 12:00	15	25	On
6/2/2023 16:00	12	27	On
6/2/2023 20:00	20	22	On

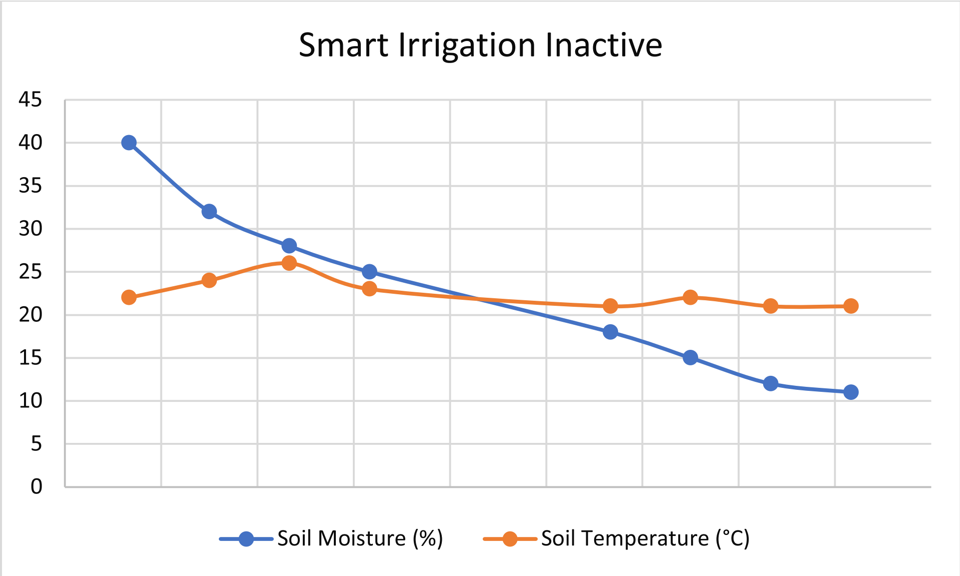

Figure 16: Variation of soil moisture and temperature with time over a 24 hour period with auto-irrigation switched on. The moisture graph has a decreasing trend, showing that the soil continuously loses moisture

4.4.2 Efficiency and Water Conservation Measures

In terms of efficiency and water conservation, the analysis revealed significant water savings compared to traditional irrigation methods. By continuously monitoring soil conditions and adjusting irrigation schedules based on plant needs, the system effectively minimized water wastage. This was further supported by the healthy growth and vitality of the plants, indicating the system's positive impact on plant health.

Table 4: Data sampled from a 24 hour period of monitoring soil moisture and temperature, with auto-irrigation switched on

TIMESTAMP	SOIL MOISTURE (%)	SOIL TEMPERATURE (°C)	WATER PUMP STATUS
6/1/2023 8:00	40	22	Off
6/1/2023 12:00	32	24	On
6/1/2023 16:00	28	26	Off
6/1/2023 20:00	35	23	Off
6/2/2023 8:00	38	21	Off
6/2/2023 12:00	30	25	On
6/2/2023 16:00	25	27	Off
6/2/2023 20:00	33	22	Off

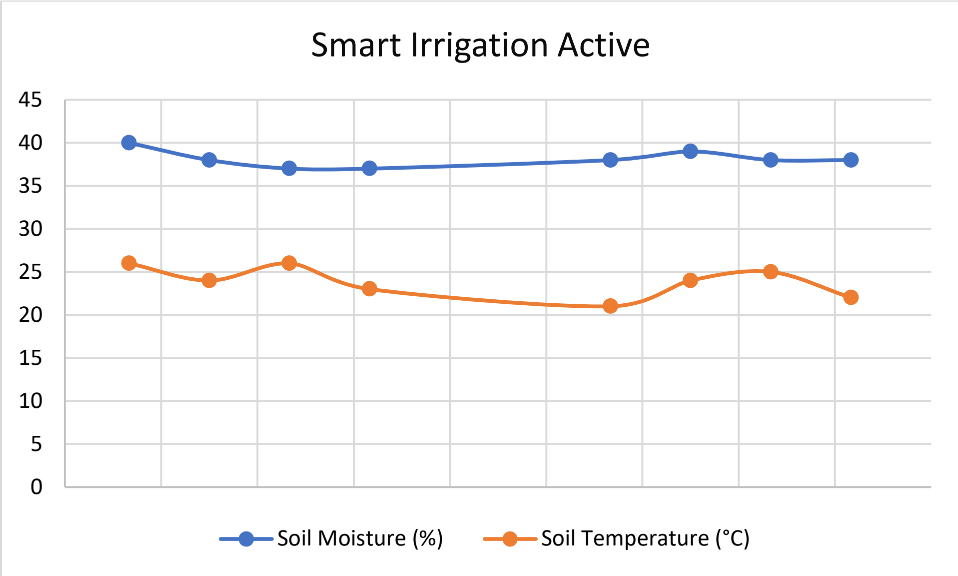

Figure 17: Variation of soil moisture and temperature with time over a 24 hour period with auto-irrigation switched on. The moisture graph is relatively flat, showing how smart irrigation is able to maintain the soil moisture almost at a constant value

Overall, the results and analysis demonstrated the successful implementation of the IoT-based smart irrigation monitoring system. It showcased its capabilities in optimizing irrigation practices, conserving water resources, and promoting sustainable agriculture. The system's reliable performance, efficiency, and water conservation measures provide a solid foundation for its practical application in various agricultural settings.

In the next chapter, I will provide a comprehensive conclusion based on the findings and insights obtained from this research. Additionally, I will discuss the contributions of this work to the field of smart irrigation systems, provide practical applications

4.5. Practical Applications and Recommendations

The IoT-based smart irrigation monitoring system developed in this research holds immense potential for practical applications in various agricultural settings. The following subsection explores the practical applications of the system and provides recommendations for its implementation.

4.5.1 Practical Applications

The system's ability to continuously monitor and optimize irrigation practices has practical applications in both small-scale and large-scale agricultural operations. Farmers can benefit from real-time data on soil moisture levels, temperature, and weather conditions to make informed decisions regarding irrigation scheduling. By automating the irrigation process based on plant needs, the system helps minimize water wastage and reduce operational costs. Additionally, the system's smart features, such as message alerts for threshold exceedance and irrigation auto-switching, provide timely interventions to ensure optimal plant health.

Furthermore, the IoT-based smart irrigation monitoring system can be applied in greenhouse farming, where precise control of irrigation is crucial for the growth and development of crops. The system's ability to monitor and adjust irrigation parameters in real time offers greenhouse farmers an efficient and sustainable solution for water management.

4.5.2 Recommendations for Implementation

Based on the findings and analysis, several recommendations can be made for the implementation of the IoT-based smart irrigation monitoring system:

Sensor Placement Optimization: To maximize the accuracy of data collection, it is essential to strategically place the soil humidity and temperature sensors. Conducting a thorough analysis of the soil properties, plant species, and environmental conditions can help determine the optimal sensor placement locations.

Weather Data Integration: Integrating weather data into the system can further enhance its capabilities. By considering weather forecasts and real-time weather data, the system can adjust irrigation schedules based on predicted rainfall or changes in temperature, ensuring efficient water management.

Expansion and Scalability: The system can be expanded and scaled up to cover larger agricultural areas. This can be achieved by deploying additional sensor nodes and establishing a robust communication network. Additionally, integrating the system with remote monitoring and control capabilities can allow farmers to manage multiple fields from a centralized location.

User Interface Enhancement: Improving the user interface of the system's dashboard can enhance its usability and accessibility. Providing intuitive visualizations, historical data analysis, and customizable settings can empower users to make informed decisions and effectively manage irrigation processes.

4.6 Final Remarks

The results and analysis presented in this chapter demonstrate the effectiveness and practicality of the IoT-based smart irrigation monitoring system. The system's performance, reliability, efficiency, and water conservation measures highlight its potential to revolutionize traditional irrigation practices. By leveraging the power of interconnected devices and real-time data analysis, the system offers farmers a smart and sustainable solution for irrigation management.

The practical applications of the system extend beyond traditional agriculture, with potential implications for greenhouse farming, urban gardening, and landscape management. Implementing the recommendations provided in this chapter can further enhance the system's performance and ensure its successful adoption in different agricultural contexts.

CHAPTER V

Conclusion

5.1. Summary of Findings

Throughout the duration of this study, a thorough development and rigorous evaluation of an IoT-based smart irrigation monitoring system was conducted. The system's architecture was comprised of state-of-the-art components, such as the ESP 8266 microcontroller featuring an integrated WiFi module, as well as soil humidity and temperature sensors, and a dependable water pump. The power of the Arduino cloud platform was utilized to craft the embedded system code with great care, ensuring uninterrupted communication and efficient data processing. Additionally, the user interface was thoughtfully designed, with visually appealing elements and intuitive navigation, resulting in a user-friendly dashboard.

The successful implementation of the system's smart features, including message alerts and irrigation auto-switching, highlights the great potential of IoT-based smart irrigation systems in transforming traditional irrigation methods. By utilizing real-time data on critical parameters such as soil moisture, temperature, and weather conditions, the system allows for precise irrigation control and optimization. The seamless integration of sensors, actuators, and communication modules enables continuous monitoring and timely adjustment of irrigation schedules, in accordance with the specific needs of the plants.

The findings of this research add substantial value to the existing knowledge regarding smart irrigation systems, showcasing the tangible benefits and practical application of IoT technologies in this field. The successful development and evaluation of the IoT-based smart irrigation monitoring system demonstrate the feasibility and benefits of implementing such systems in agricultural settings. The system's ability to gather real-time data and make informed irrigation decisions has the potential to improve water management practices, increase crop yield, and enhance resource efficiency.

Moreover, the integration of IoT technologies in smart irrigation systems holds tremendous promise in addressing critical agricultural challenges, such as water scarcity and environmental sustainability. By providing precise and optimized irrigation control, these systems reduce water wastage and decrease reliance on traditional methods that often result in inefficient water usage. The ability to adapt irrigation schedules based on real-time data mitigates the risks associated with under- or over-watering, promoting healthy plant growth while conserving valuable resources.

The successful development and evaluation of the IoT-based smart irrigation monitoring system establishes the groundwork for further advancements and research in this area. Future studies can explore the integration of additional sensors and technologies to provide a more comprehensive understanding of the crop environment and further improve irrigation precision. Collaboration between researchers, industry professionals, and policymakers is vital to facilitate the widespread adoption and implementation of smart irrigation systems, ensuring that their potential benefits are realized on a larger scale.

The successful development and evaluation of the IoT-based smart irrigation monitoring system underscores the importance of real-time data collection, precise irrigation control, and resource optimization. By leveraging IoT technologies, these systems can enhance water management practices, improve crop yield, and promote sustainability in agriculture. Continued research and collaboration are essential to further advance this field and facilitate the widespread adoption of smart irrigation systems in the pursuit of a more sustainable and efficient agricultural future.

5.2 Contributions in the Domain

This study brings forth various contributions to the realm of intelligent irrigation systems. Firstly, it provides a practical implementation of an IoT-based smart irrigation monitoring system using readily available components. The system's design and development process can serve as a reference for researchers, engineers, and practitioners interested in building similar systems.

Secondly, this study highlights the importance of data-driven decision-making in irrigation management. By leveraging sensor data, the system enables informed irrigation scheduling, reducing water wastage and improving overall efficiency. The incorporation of message alerts and automation further enhances the system's intelligence and ease of use.

Additionally, the research contributes to the existing body of knowledge on IoT technologies and protocols for smart agriculture applications. By utilizing the Arduino cloud platform, the study showcases the capabilities of such frameworks in facilitating device connectivity, data exchange, and visual design features.

5.3 Practical Applications and Recommendations

The practical applications of the IoT-based smart irrigation monitoring system are numerous. It can be employed in various agricultural settings, ranging from small-scale gardens to large-scale farms. By providing real-time data on soil conditions and weather, the system empowers farmers and growers to make informed decisions regarding irrigation, leading to optimized water usage and improved crop health.

To further enhance the system's functionality, future research and development can focus on expanding its capabilities. For instance, incorporating additional sensors to measure factors such as light intensity, humidity, and nutrient levels can provide a more comprehensive understanding of the crop environment. Integration with weather forecasting services can enable proactive irrigation planning based on predicted weather patterns.

Furthermore, collaboration between researchers, industry professionals, and policymakers is essential to promote the adoption and widespread implementation of smart irrigation systems. Education and training programs can help raise awareness about the benefits of these systems and provide the necessary skills for their installation and maintenance.

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Appendices

Appendix A: Source Code

The source code, data, and thesis file are available in the GitHub repository:

https://github.com/ahmedcontehneu/mythesis/

Appendix B
List of papers from the Thesis

[1] Conteh, A., & Al-Turjman, F. (2022). A review of artificial intelligence of things. The International Conference on Forthcoming Networks and Sustainability (FoNeS 2022). https://doi.org/10.1049/icp.2022.2559.

Other Publications

See attached CV

Appendix C

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