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Intelligent drip irrigation: leveraging embedded systems and sensor networks for real-time monitoring and fault diagnosis

N. Kalidas[1*], Dr.S. Goshteeswaran[2], Muhamed Hussain[3], Kiran Kumar Mamidi[4], Dr. Srinivas Rao Kondaveeti[5]

[1*]*Department of Mechanical Engineering, Karpagam Academy of Higher Education, Coimbatore, 641021, India*
[2]*Department of Mechanical Engineering, Karpagam Institute of Technology, Coimbatore, 641105, India*
[3]*Department of Structurals Techniques Engineering, College of Technical Engineering, The Islamic University, Najaf, Iraq; Department of Structurals Techniques Engineering, College of Technical Engineering, The Islamic University of Al Diwaniyah, Al Diwaniyah, Iraq; Department of Structurals Techniques Engineering, College of Technical Engineering, The Islamic University of Babylon, Babylon, Iraq*
[4]*Department of AIMLE, GRIET, Hyderabad, Telangana, India*
[5]*Professor, Department of Mechanical Engineering, CMR College of Engineering & Technology, Hyderabad, Telangana, India*

Abstract. Recent advancements in wireless sensor networks (WSNs) and precision agriculture have captured significant interest in both research and industry. Integrating WSNs into agriculture offers numerous benefits, including enhanced crop quality, improved production efficiency, resource conservation (water and energy), and optimized crop management practices (such as irrigation and fertilization). Irrigation, a crucial factor for agricultural success, is often hampered by current systems' inefficiencies and rising production demands. Water scarcity, drought, and limited water resource waste further complicate conventional irrigation. To address these issues, we propose an intelligent irrigation system prototype that combines WSN technology with drip irrigation. This system utilizes WSNs and ZigBee wireless communication to create an automated and intelligent irrigation solution that conserves water, enhances irrigation system performance, and improves efficiency. Sensor data collected from strategically placed sensors near plant roots (including temperature and soil moisture) is used to control irrigation. The system analyses this data against predefined thresholds for each parameter and activates or deactivates irrigation accordingly. This approach aims to achieve significant water, time, and energy savings.

1 Introduction

Agriculture underpins human development, economic growth, and food security. It sustains billions globally, contributes significantly to national income in developing countries, and provides food for people and animals. However, rising food demands due to population growth necessitate innovative solutions. Integrating new technologies like wireless sensor

* Corresponding author: kalidas.natarajan@kahedu.edu.in

networks, the Internet of Things (IoT), and cloud computing into agriculture offers immense potential for improved data collection, processing, and decision-making, leading to higher productivity. Sensor networks play a crucial role in precision agriculture practices like irrigation, fertilization, and pest control. Irrigation, in particular, is essential for ensuring crop yields and high-quality food production. While it's vital for feeding the growing population, current irrigation systems often face inefficiencies due to water evaporation, leaks, and losses. Implementing new technologies can significantly improve water usage. This paper proposes an intelligent irrigation system that leverages wireless sensor networks and ZigBee communication to create a remote control system for farmers. Our system combines drip irrigation with sensor technology to monitor soil moisture, temperature, and air conditions. By analysing this data against predefined thresholds, the system automatically activates or deactivates irrigation, aiming to optimize water usage.

2 Background

2.1 Irrigation systems: a crucial aspect of agriculture

Irrigation is the artificial application of water to land to supplement or replace natural rainfall. It's essential for agriculture, especially in arid or semi-arid regions, to boost crop production and development. There are three main irrigation system categories:

- Surface irrigation: The oldest and most traditional method, relying on gravity flow to distribute water across the soil surface.
- Sprinkler irrigation: Mimics rainfall by spraying water uniformly over the field, similar to natural precipitation.
- Drip irrigation: A modern, water-efficient system that delivers small amounts of water directly to the root zone of plants through a network of pipes and emitters. This approach minimizes water waste due to evaporation and runoff, making it ideal for drier climates. Drip irrigation offers several advantages, including water conservation, reduced weed growth, and more precise water application.

2.2 Wireless sensor networks: revolutionizing data collection

Advancements in technology, particularly the miniaturization enabled by Micro-Electro-Mechanical Systems (MEMS), have led to a surge in interest in Wireless Sensor Networks (WSNs) in recent decades. These networks consist of inexpensive, intelligent sensors with minimal size and built-in processing capabilities. They can be densely deployed across an area to gather and share data cooperatively. WSNs function as a specific type of Ad-Hoc network, with numerous sensor nodes communicating wirelessly to share information. Sensor networks perform three core tasks: sensing, data communication, and computation. Sensors scattered throughout a field collect data to create a comprehensive picture of the monitored environment. This information is then routed directly or through nearby sensors to a central collection point called a base station for further processing. The base station can also act as a gateway for communication with external networks, as illustrated in Figure 1.

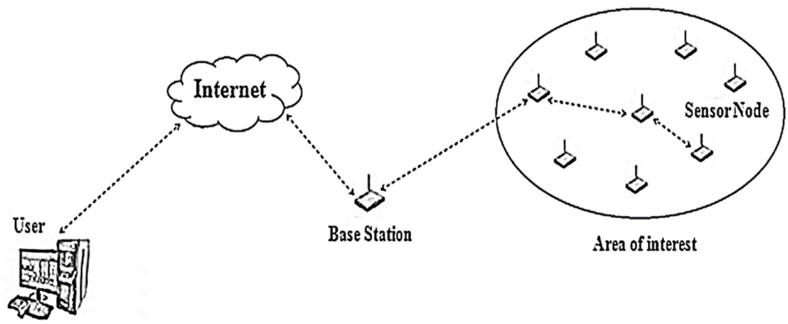

Fig. 1. WSN (Wireless Sensor Networks)

2.3 Wireless sensor networks: from military applications to diverse fields

While Wireless Sensor Networks (WSNs) were initially developed for military purposes like battlefield surveillance, their versatility and technological advancements have opened doors for applications in numerous sectors. WSNs excel at gathering and processing environmental data, making them valuable tools across various domains. Existing literature explores a wide range of current and potential WSN applications [1]. These applications span military, agriculture, environmental monitoring, industrial automation, automotive systems, and even medical devices. The foundation of WSNs lies in sensors, miniaturized, autonomous devices equipped with advanced sensing capabilities. Despite limitations in processing power, storage, and energy, these networked sensors work together to collect and transmit data to a central base station [2]. Each sensor typically comprises four key units, as illustrated in Figure 2.

- Sensing Unit: This core component houses two sub-units: a sensor that gathers measurements from the environment and an Analog-to-Digital Converter (ADC) that transforms the captured information into a format suitable for processing.
- Processing Unit: This unit includes a processor (computing unit) for performing basic calculations and collaborating with other sensors, as well as memory (storage unit) for a specialized operating system.
- Transmission Unit (Transceiver Unit): This unit manages all data transmissions and receptions using a radio communication medium. The type can be optical (e.g., Smart Dust or radio frequency (e.g., MICA2 [3]).
- Power Unit (Battery): Each sensor relies on a battery to power all its components.

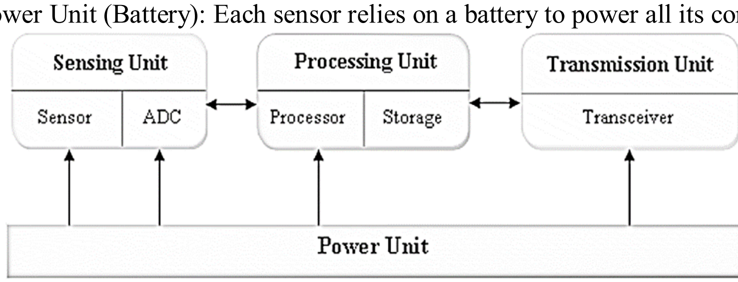

Fig. 2. Architecture

Several wireless communication technologies, including Wi-Fi, Bluetooth, and ZigBee, are explored in various WSN research projects. Each offers unique characteristics. In our system, ZigBee is chosen due to its well-suited features for our application. ZigBee, a technology developed by the ZigBee Alliance, builds upon the IEEE 802.15.4 standard to define higher-level communication protocols for low-power Wireless Personal Area Networks (WPANs). It prioritizes simplicity, affordability, and ease of use compared to other WPAN options. ZigBee's focus on low power consumption limits its typical transmission range to 10-100 meters, depending on output power and environmental factors. However, it supports mesh networking, where data can be relayed through intermediate devices to reach distant nodes. This is ideal for our application where long-range communication may be necessary. ZigBee excels in applications requiring low data rates, secure communication, and extended battery life. It employs 128-bit symmetric encryption for robust security and offers a data rate of 250 kbps, well-suited for intermittent data transmissions from sensors. Additionally, ZigBee boasts key advantages like self-organization, multi-hop mesh networking, and low cost, leading to longer battery life for sensor nodes – a critical factor in our system.

3 Literature survey

Water scarcity necessitates improved irrigation management to prevent waste. Traditional systems often lack efficiency, but this can be addressed by leveraging data on soil, climate, and surrounding environment. Wireless Sensor Networks (WSNs) are proving to be a powerful tool for enhancing irrigation system effectiveness. Numerous research projects have explored WSN integration for irrigation control. Damas et al. [4] presented a remote-controlled system for large areas in Spain, achieving significant water savings (30-60%). Kim et al. [5] developed decision-support software that integrates with a WSN for real-time sprinkler irrigation control using Bluetooth communication. Morais et al. [6] implemented an intelligent irrigation system in Portugal that utilizes wireless data acquisition stations to gather climate and soil moisture data, leading to improved irrigation efficiency and crop yields. Gutiérrez et al. [7] proposed an automated system using a WSN and GPRS module to manage irrigation water. This system employs a network of sensors near plant roots to monitor soil moisture and temperature. The collected data is transmitted to a central unit for analysis and irrigation activation based on predefined thresholds. Stefanos et al. [8,9,10] presented an energy-efficient WSN routing protocol (ECHERP) for an automated irrigation system that calculates water needs based on soil moisture content. Further research by Troy Peters et al. [11] involved integrating a WSN with a control and decision-support system to manage irrigation for an apple orchard. Their system, utilizing soil, weather, and thermal sensors, achieved a reduction in applied water of up to 70%. Işik et al. developed a precision irrigation system that integrates sensor networks with a mobile app (iOS/Android) for real-time monitoring and control based on plant water requirements at different growth stagesm [12]. Alvino and Marino conducted a comprehensive survey on remote sensing applications for irrigation management, highlighting various techniques, systems, approaches, and challenges. Additionally, described an intelligent system for controlling bicarbonate levels in irrigation for hydroponic agriculture using WSNs and auto-calibrated pH sensors [13]. This research demonstrates the significant potential of WSNs in optimizing irrigation systems, leading to water conservation and improved agricultural productivity.

4 Proposed system

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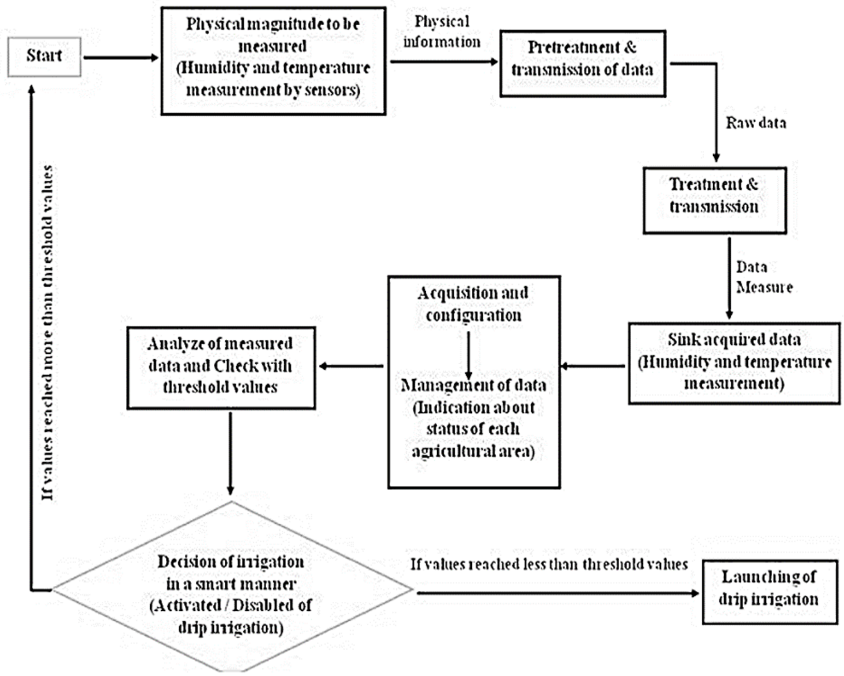

Fig. 3. Flowchart

Conventional irrigation systems struggle with increasing water scarcity, rising production demands, and inefficiencies. To address these challenges, we propose a smart irrigation system that integrates Wireless Sensor Networks (WSNs) and ZigBee communication for automatic irrigation control [14]. This system utilizes drip irrigation, the most efficient method identified through a comparison of existing systems, due to its water savings, reduced evaporation, and automation potential. ZigBee was chosen as the most suitable communication technology due to its efficiency for WSNs, considering our system's limited memory and computing needs. Soil moisture and temperature are critical parameters, and we will employ EC-5 and DS18B20 sensors to monitor these along with air temperature and humidity [15,16]. By analysing this sensor data against predefined thresholds (adjustable based on crop type), the system automatically activates or deactivates irrigation. This intelligent system leverages WSNs, ZigBee communication, and sensor technology to create a remote control system for farmers. Our prototype divides the irrigated land into smaller sections to extend the WSN lifespan. In each section, sensors monitor soil moisture and temperature, and air conditions. Sensor data is transmitted to a central base station for processing and storage [17]. Based on comparisons with predefined thresholds, the system triggers irrigation activation for dry areas. A use case diagram (Fig. 5) illustrates the system's actors and their interactions. This integration of drip irrigation, WSNs, and ZigBee offers a smart and automatic irrigation solution [18].

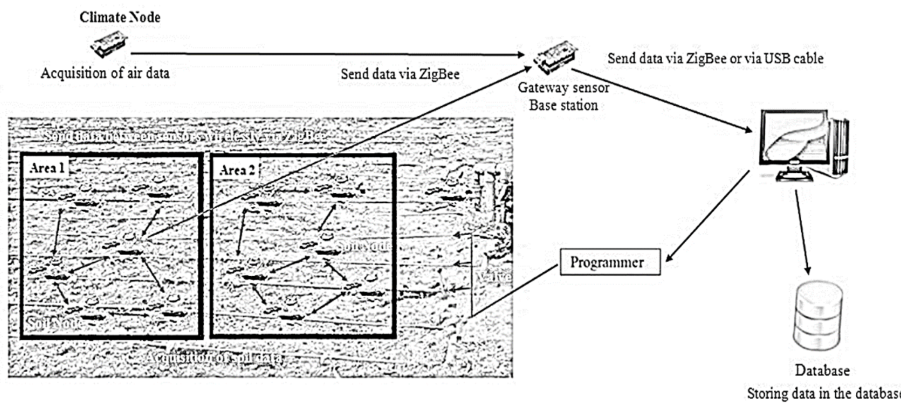

Fig. 4. Prototype

5 Sensitivity of sensors

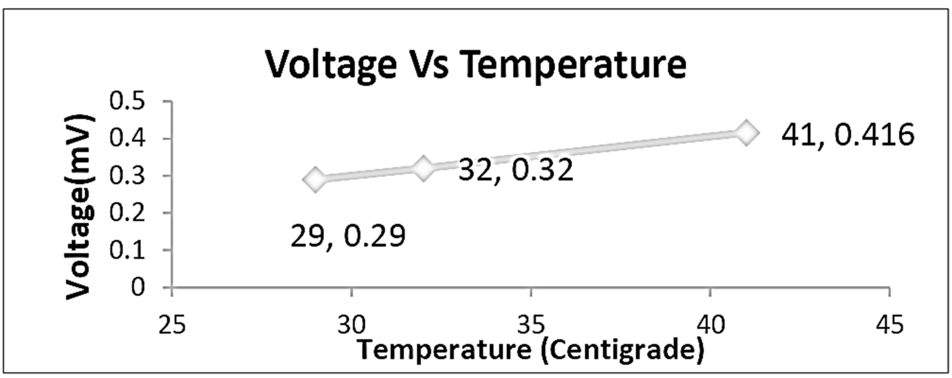

Fig. 5. Sensitivity (Temperature Sensor)

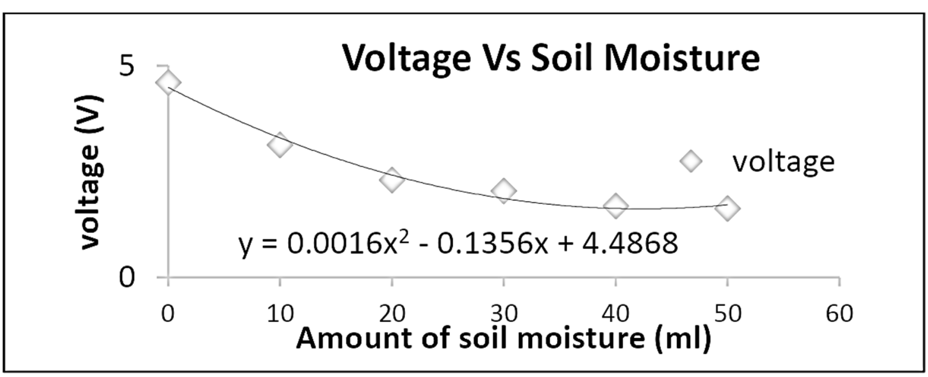

Fig. 6. Sensitivity (Soil Moisture Sensor)

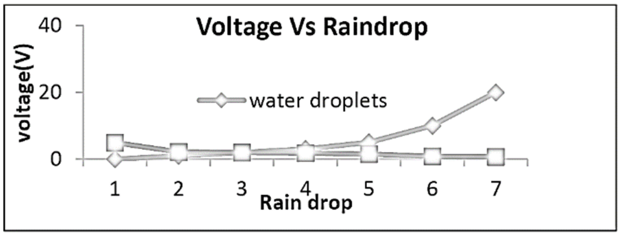

Fig. 7. Sensitivity (Raindrop Sensor)

6 Results

The system relies on soil moisture levels to determine irrigation activation. When the soil moisture sensor detects a level below 51%, the sensor voltage is amplified. This amplified voltage is then sent to the controller. Simultaneously, the rain sensor board detects the presence or absence of rain [19]. If the soil moisture is low (below 51%) and it's not raining, the amplified voltage is sufficient to trigger the relay and activate the pump. The LCD display will reflect this action by showing "PUMP ON" and "NO RAIN." [23-25]Conversely, if the soil moisture is above 51%, regardless of rain conditions, the voltage is insufficient to activate the relay. The pump remains off, and the LCD displays "PUMP OFF" along with either "RAINING" or "NO RAIN [20]."

Soil Condition	Board Condition	Pump Condition
>51%	"RAINING"	"PUMP OFF"
>51%	"NO RAIN"	"PUMP OFF"
<51%	"RAINING"	"PUMP OFF"
<51%	"NO RAIN"	"PUMP ON"

7 Conclusion

The rise of wireless sensor networks (WSNs) has opened doors for innovative applications in various fields, including environmental monitoring and analysis. In agriculture, ensuring sustainability is critical, particularly with the global water crisis looming. Irrigation systems, vital for agricultural development, present an opportunity for improvement. This paper proposes an intelligent irrigation system leveraging WSNs and ZigBee communication technology. We present a prototype of this smart irrigation system, detailing its operation, architecture, and design. Our solution enables intelligent irrigation control by monitoring soil and weather parameters. Based on this data, the system autonomously decides to activate irrigation, aiming to optimize irrigation efficiency, performance, and water conservation.

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