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Mobile Solar Powered Irrigation System

Shriraj Joshi[1], Samruddhi Kadam[2], Ashutosh Adasr[3]
Department of E&TC Engineering AISSMS Institute of Information Technology Pune, India

Abstract: Water scarcity and rising fossil fuel prices present challenges to the global agricultural community. Conventional irrigation systems frequently depend on erratic power sources, are inefficient, and are stationary. This study suggests a mobile solar-powered irrigation system that maximizes energy and water resources. A solar panel for renewable energy, a DHT22 and pH sensor for water and environmental health analysis, and a Bluetooth module for local control are all integrated into the system using an ESP32 microcontroller. Additionally, the Webserver interface enables remotely accessing and managing the system.Using of Soil Moisture sensor for detection of water in soil for proper irrigation. The mobile feature of the system also enables it to irrigate several plot areas with a single unit, which is a major cost-saving factor. Preliminary results indicate that the system improves crop production while minimizing environmental degradation through data-driven irrigation. In the aftermath of worldwide climate change and the depletion of freshwater resources, the agricultural community is under a critical mandate to upgrade and modernize. Traditional irrigation systems are marked by inefficiency, labor intensity, and dependence on fossil fuel-based electricity. This research paper proposes a new Mobile Solar-Powered Irrigation System that combines the ESP32 microcontroller, IoT (Internet of Things) technology, and Android mobile control. Unlike traditional irrigation systems, this proposed system has a moveable chassis that is driven by renewable solar energy and can irrigate divided land parcels. The system uses a DHT22 sensor for environmental monitoring and a pH sensor mechanism for ensuring the availability of water nutrients. The data is transmitted through a Bluetooth module for local control and a Webserver for remote analysis. The proposed system design is cost-effective, scalable, and energy-independent, which optimizes water and crop yields to a great extent.

Index Terms: Mobile irrigation system, Solar-powered system, ESP32, Internet of Things (IoT), Smart agriculture, Precision irrigation, Water pH monitoring, Soil moisture sensing, Wireless communication, Embedded systems, Renewable energy, Automation in agriculture

I. INTRODUCTION

A. General Background

Agriculture has always been the backbone of civilization, and in many developing nations, it still remains the main source of livelihood for the vast majority of people. However, the agricultural sector is presently at a crossroads. The twin challenges of a growing global popula-tion, estimated to reach 9.7 billion by 2050, and the fluctuating weather patterns due to climate change are leading to a demand for food production that has never been witnessed before. In this case, the agricultural sector must move from traditional farming to technology-based farming.

Water scarcity is perhaps the biggest challenge to food security. Traditional irrigation methods, such as flood irrigation or manual irrigation, have been found to be inefficient. Studies have revealed that nearly 30% to 50% of the water utilized in traditional agricultural systems is lost due to evaporation, runoff, or misallocation depends upon weather condidton. In addition, the dependence on fossil fuels and unstable power supply for the pumping of water adds a new cost factor to the farmers, apart from the increased carbon footprint of the agricultural supply chain.

It is in this context that the requirement for ”Smart Agri-culture” or ”Agriculture 4.0” has been recognized as a key solution. This model integrates the Internet of Things (IoT), renewable energy, and automation to provide solutions that are more than just tools, but rather intelligent assistants that can gives the values and helps to take decision.

B. Motivation and Problem Statement

Although auto-mated irrigation systems are available in the market, their usage is limited among small to medium-scale farmers.

The reason for this is the presence of three limitations in the current systems:

- Stationary System: Most commercial automated irriga-tion systems are fixed. A farmer with multiple small plots of land cannot afford to install separate sensor nodes and control units for every acre of land. This makes the ”smart” system a cost-prohibitive technology for the average farmer.

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- Energy Dependence: In many rural areas, electricity is either not available or available in erratic hours (usually at night). Diesel pumps provide an alternative, but they are costly to run and harmful to the environment. There is a definite need for an energy-independent system.
- Lack of Irrigation Water Quality Testing: Although most automatic irrigation systems mainly rely on soil moisture testing, they do not pay much attention to the pH level of the irrigation water. The pH level of the

Table I
Comparative Analysis Of Irrigation Systems

Feature	Traditional	Static Smart (IoT)	Proposed Mo-bile Solar
Power Source	Grid / Diesel	Grid / Solar Hybrid	100% Off-Grid Solar
Mobility	Fixed In-frastructure	Fixed Sensor Nodes	Fully Mobile Rover
Sensor Coverage Cost	High (Man-ual Labor)	High (Per-Zone Node)	Low (Shared Unit)
Data Logging	None	Cloud / Web-server	Cloud / Web-server
Water Quality (pH)	Manual Testing	Rarely Integrated	Automated pH Sensor
Water Efficiency	Low (~50% Loss)	High	Very High (Precision)

irrigation water is important for ensuring the health of the soil and its fertility. If the wrong pH of the irrigation water is supplied consistently, it will affect the soil's ability to hold nutrients and hinder the efficiency of fertilizers, resulting in poor plant development.

C. Project Overview and Objectives

In order to over-come these issues, this research work aims at the design and development of a Mobile (Moveable) Solar-Powered Irrigation System. This project goes beyond the idea of fixed automation by mounting the irrigation system on a robotic platform. This ”rover” is intended to move between various zones of a farmland, harnessing the power of renewable solar energy to propel itself, its sensors, and water pump.

The primary aims of this project are:

- To Design a Mobile Platform: Designing a robust, wheeled base capable of supporting a water pump, battery, and sensor module over agricultural land, thus reducing the need for multiple fixed systems.
- To Integrate Renewable Energy Sources: The system is fully off-grid and environmentally friendly, making it perfect for use in remote areas, by using the energy from a solar panel to charge an onboard battery.
- To Facilitate Precision Monitoring:using a mechani-cal pH sensor probe to measure soil composition and a DHT22 sensor to measure ambient temperature and humidity. for analyzing soil composition. This ensures that irrigation occurs only when necessary due to unfa-vorable environmental conditions (high temperature, low humidity), and that the soil is healthy.
- To Establish Dual-Layer Communication: Develop-ment of a dynamic control interface with Bluetooth for short-range, manual control using an Android app, and Webserver for long-range data logging and remote monitoring using Internet of Things (IoT).

D. Scope of the Study

The project will be based on the development of a functional prototype to test the concept of mobile and solar-powered irrigation. The scope of the study will include the hardware implementation of the ESP32 microcontroller with HC-05 Bluetooth module and ESP32 Wi-Fi module, as well as the software logic required for the automation of the irrigation process based on sensor thresholds. The study will also include the development of an Android interface and web interface for data analysis. Even though the prototype will be developed on a small scale, it can be scaled up for agricultural purposes. This project has the potential to offer a sustainable and cost-effective roadmap for farming's future—one that uses technology to safeguard our most valuable resources, energy and water—by integrating mobility, solar power, and smart sensing.

II. LITERATURE REVIEW

Smart irrigation systems have received considerable focus due to their implementation of IoT technology, machine learning, and renewable energy for efficient use of water and improvement of agriculture production levels.

As mentioned in [1], the state-of-the-art smart irrigation systems make use of intelligent sensors, soil moisture sensing and analytics. The use of IoT architecture and artificial neural networks for optimization of the irrigation process is empha-sized in this paper; yet, mobility has not been considered by authors.

The article in [2] is dedicated to the development and testing of a smart irrigation system using solar power. It proves its sustainability and energy efficiency. Still, this system is rather immobile and cannot adapt to any other environment.

IoT-based irrigation systems considered in [3] – [5] are implemented by means of sensor networks along with cloud platforms in order to enable automatic control of the irrigation process. They prove to be rather efficient in water saving and monitoring. Yet, they cannot be used in places with poor network connections.

The use of embedded system-based solutions, as shown in [6] by developing an ESP32-based drip irrigation system, provides a cost-effective and scalable solution. Even with the advantages of using an embedded system-based solution, the system cannot be mobile since it is only designed for fixed installations.

In terms of mobile irrigation systems, research was done in [7] and showed that mobile irrigation systems offer better performance regarding uniform water distribution depending on the environmental condition. Although mobility enhances irrigation efficiency, the lack of incorporation of renewable energy makes the system unsustainable in the long term. Another research paper on irrigation, [8], discusses a solar-based irrigation system incorporated with micro-irrigation methods. The paper highlights the efficiency of the system in uneven terrain but fails to incorporate advanced features such as automation and intelligent control techniques.

Machine learning irrigation systems in [10] and [15] have been used in predictive decision making by using environmental parameters. Although machine learning helps

TABLE II
COMPARATIVE ANALYSIS OF EXISTING SMART IRRIGATION SYSTEMS

Ref	Focus of Existing Work	Major Result	Limitation	Proposed Improvement
[1]	Smart irrigation overview	Comprehensive architec-ture for smart farming	Mostly theoretical, no implementa-tion	Mobile solar-based practical sys-tem
[2]	Solar-powered irrigation (urban farming)	Energy-efficient irrigation using solar	Static system, no mobility	Mobile irrigation rover
[3]	IoT + ML irrigation	Intelligent decision-making	High computation, complex	Lightweight control system
[4]	Smart irrigation overview	IoT-based monitoring models	No real-time prototype	Practical embedded implementa-tion
[5]	IoT irrigation system	Automated irrigation con-trol	Limited parameters	Multi-sensor integration
[6]	ESP32 drip irrigation	Low-cost IoT solution	Fixed installation	Mobile deployment
[7]	Movable irrigation opti-mization	Improved water distribu-tion	No renewable energy	Solar-powered mobility
[8]	Solar irrigation in hilly re-gion	Efficient irrigation perfor-mance	Limited automation	Smart autonomous control

[9]	Irrigation system review (Kenya)	Identifies system challenges	No hardware design	Practical implementation
[10]	ML-based irrigation	Predictive irrigation deci- sions	High complexity	Simplified logic-based control
[11]	Irrigation management re- view	Water saving strategies	No real-time control	Automated irrigation system
[12]	Smart irrigation strategies	Improved water efficiency	Infrastructure dependency	Standalone system
[13]	Cloud + IoT irrigation	Remote monitoring	Server dependency	Edge-based processing
[14]	IoT irrigation system	Automation using sensors	Limited novelty	Mobility + solar integration
[15]	ML irrigation system	Precision agriculture	High cost	Cost-effective system
[16]	IoT monitoring	Basic automation	No mobility	Mobile irrigation system
[17]	Smart irrigation technolo- gies	Improved water usage	Conceptual study	Hardware implementation
[18]	IoT agriculture system	Real-time monitoring	No actuation	Full irrigation control
[19]	AI irrigation	Smart decisions	Complex algorithms	Simple rule-based control
[20]	IoT irrigation overview	Climate-based irrigation	Less adaptable	Multi-condition system
[21]	Solar irrigation kit	Renewable energy usage	Limited sensing	Multi-parameter sensing
[22]	Energy-efficient irrigation	Sustainable agriculture	Expensive solutions	Low-cost system
[23]	Solar irrigation automa- tion	Pump automation	No mobility	Mobile irrigation rover
[24]	Fuzzy logic irrigation	Intelligent control	Complex tuning	Simplified automation

to increase irrigation efficiency, it adds computational complexity and cost compared to other irrigation techniques. Several review papers have been written to highlight the significance of using smart irrigation strategies in precision agriculture, including [11], [12], and [20].

As mentioned in [13], IoT-integrated cloud irrigation systems facilitate monitoring and control from a distance.

Nevertheless, the use of cloud architecture results in increased latency and unreliability of services in rural areas. Solar-powered irrigation systems proposed in [21] and [22] illustrate the advantages of using renewable power sources in terms of decreasing expenses and minimizing ecological footprint. Unfortunately, these devices are mostly fixed and lack mobility capabilities.

Modern control algorithms, such as fuzzy logic-based systems described in [24] and automatic irrigation schemes outlined in [23], provide better results compared to manual controls. Nevertheless, they require precise tuning and configuration.

III. SYSTEM ARCHITECTURE AND COMPONENTS

A. Overview of System Design

The proposed Mobile Solar-Powered Irrigation System is designed as a modular, autonomous robotic system. The system is designed with a centralized microcontroller unit that communicates with three different subsystems:

1) The Power Subsystem: Deals with renewable energy resource harvesting and management.
2) The Sensing & Actuation Subsystem: Deals with environmental sensing and physical actuation (pumping and motion).

3) The Communication Subsystem: Enables local control through Bluetooth and remote data logging through a Webserver.

The communication between the subsystems allows the system to operate as a single ”Smart Farm” system that can make autonomous decisions based on real-time environmental inputs.

$$P_s = A \times G \times \eta \qquad (1)$$

Meaning

- Ps = Solar panel power output (W)
- A = Solar panel area (m²)
- G = Solar irradiance (W/m²)
- n= Panel efficiency

This equation explains how solar energy is generated for the system.

B. Hardware Components

1) Central Processing Unit:

- ESP32: The system’s central component is the ESP32 , a microcontroller board based on the microcontroller.
- Role: It functions as the ”brain” of the system, managing communication protocols, executing control algorithms, and interpreting sensor inputs.
- Justification from Technical Standpoint: The ESP32 mi-crocontroller was chosen based on its superior perfor-mance, built-in capabilities of Wi-Fi and Bluetooth, and low power requirements. Having a clock frequency of 240 MHz, this microcontroller can work effectively with sensor data and perform necessary control actions without an operating system running. Also, a 3.3V logic level allows compatibility with any sensors, whereas external driver circuits were added for the communication with motor-driven actuators and relays. Moreover, the ESP32 microcontroller has many GPIO pins and ADC, which is enough for the connection of all sensors and actuators..

2) Power Supply Unit (PSU):

The system is built to be energy self-sustaining, using a ”Harvest-Store-Consume” approach.

- Solar Panel: The solar panel comprises four 6V, 100mA PV panels that are placed on the top of the chassis to capture solar energy and transform it into electrical energy. The four panels are wired in 2 in series 2 in parallel combination such that two panels are wired in series to boost up the voltage and the two strings in parallel are boosted up to produce 0.2A of current. This design gives an estimated output of 12V and 0.2A of current during peak sunlight conditions, giving a total power output of 2.4W. The energy generated by the solar panels is used mainly for charging the battery and pow-ering other low-current-consuming electronics like the microcontrollers, sensors, and communication devices. However, the current from the solar panels cannot be used directly to provide power to the load because of its low output current compared to the water pump load. Consequently, the use of a buck converter will ensure the regulation of the voltage from the solar panels for charging the batteries. Although the solar panels will not power the load directly, their presence is essential for balancing the energy of the system.
- Battery Storage: A dual battery storage system using Lithium-Polymer (Li-Po) cells is implemented to ensure reliable operation under varying environmental conditions such as low sunlight or cloudy weather. The system consists of two separate battery packs: the first pack contains three 3.7V, 2000mAh cells connected , providing a nominal output of approximately 11.1V, and is dedicated to powering sensors and the ESP32 microcontroller. The second pack consists of two 3.7V, 2000mAh cells , delivering approx-imately 7.4V, and is used to supply power to the motor driver and associated load. Solar energy harvested from the photovoltaic panels is regulated using an XL4015 DC-DC buck converter, which steps down and stabilizes the voltage to suitable charging levels. The regulated output from the buck converter is then distributed to both battery packs for charging. This dual-pack configuration ensures load separation, improved stability, and efficient power management, allowing sensitive electronics and higher power components to operate without mutual interference while maintaining continuous system functionality. .

$$E_b = V \times Ah \qquad (2)$$

- Meaning
  - Eb = Stored battery energy (Wh)
  - V = Battery voltage
  - Ah = Battery capacity

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3) Sensing Unit

For simulating the decision-making of an experienced farmer, the system uses two major sensors:

- DHT22 Sensor: Unlike the more affordable DHT11, the DHT22 was selected for its greater accuracy (±0.5°C temperature and ±2-5% humidity accuracy) and greater range (-40 to 80°C). It employs a capacitive humidity sensor and a thermistor to detect the ambient air. This information is essential as high temperatures and low hu-midity accelerate evapotranspiration, raising the water demand of the crop.

- Meaning

$$pH = 7 + \frac{Vout - Vneutral}{k} \quad (3)$$

  - Vneutral = Neutral voltage at pH 7
  - k = Calibration constant
  - Vout = Sensor voltage output

- pH Sensor Working Principle: The acidity or basicity of water is an essential parameter that needs to be maintained at optimal levels for optimal plant growth. A wrong pH balance in the water can slowly impact the nature of soil and its nutrients. In this project, an industrial analog pH sensor is employed to determine the pH of the irrigation water. *Mechanism:* As it would be destroyed by being pulled through the soil, the probe is fixed to a Servo Motor arm. When the robot comes to a halt, the servo deploys the probe into the soft, pre-tilled soil to get a reading, then withdraws it before resuming motion.

- Meaning

$$Q = \frac{}{t} \quad (4)$$

  - Q = Water flow rate (L/min)
  - V = Volume of water delivered
  - t= Irrigation time

TABLE III
HARDWARE COMPONENTS AND TECHNICAL SPECIFICATIONS

Category	Module	Technical Specifications	Primary Function
Microcontroller	ESP32 DEV KIT (2 Units)	ESP32, 240MHz, 3.3V logic, built-in Bluetooth	One unit for sensor interfac-ing and IoT communication; sec-ond for mobility and control via Bluetooth
Power System	Solar Panel Array	4 Panels (6V, 100mA each), con-figured as 2S2P	Renewable energy harvesting
Power System	LiPo Battery Packs	2 Packs: (3-cell and 2-cell), each cell 3.7V, 2000 mAh	Energy storage and supply to system modules
Power System	Buck Converter (XL4015)	5A DC-DC Converter; Regu-lated Output: 5V/12V	Voltage regulation and battery charging control
Sensors	DHT22	Temp: -40–80°C (±0.5°C), RH: 0–100% (±2%)	Micro-climate monitoring
Sensors	Analog pH Sensor (Water Quality)	Range: 0–14 pH; Accuracy: ±0.1 pH at 25°C; Operating Voltage: 3.3–5V	Water acidity/alkalinity monitor-ing

Sensors	Soil Moisture Sensor	Operating Voltage: 3.3V–5V; Output: Analog (ADC-based)	Soil moisture level detection for irrigation control
Mobility	DC Gear Motors (4x)	12V DC, 300 RPM, High Torque	Rover locomotion
Driver	L298N Motor Driver	Dual H-Bridge Motor Driver, 12V operation	Motor control and power ampli-fication
Actuation	Submersible Pump	12V DC; Flow Rate: 3–5 L/min	Controlled irrigation delivery
Actuation	Relay Module (2-Channel)	5V Relay Module	Switching control for pump op-eration
Actuation	Servo Motor	5V DC, Angular Rotation (0–180°)	Positioning of soil moisture sen-sor
Communicatio n	ESP32 DEV KIT and HC-05	Bluetooth 2.0 (2.4 GHz); Wi-Fi 802.11 b/g/n	Local control and IoT data log-ging
Display	LCD Display	16x2 LCD, 5V operation	Real-time display of sensor pa-rameters

4) *Actuation and Mobility Unit:*
- Motor Driver (L298N): The ESP32 GPIO pins do not source sufficient current to power motors. The L298N Dual H-Bridge Driver enables the low-current control signals from the ESP32 to control the high-current power from the battery to the motors. It controls the direction and speed of the robot.
- DC Gear Motors: Four high-torque DC Gear Motors (300 RPM) are used for traction. The low RPM and high torque are critical for the robot to move on uneven agricultural land without stalling.
- Submersible Water Pump: A small 12V DC Pump is used for water supply. It is turned on/off using a 2 channel 3.3V Relay Module, which keeps the high-voltage pump circuit isolated from the microcontroller logic.

C. *Communication Architecture*

The system uses a Hybrid Communication Topology for redundancy and ease of access.

1) *Local Link: Bluetooth (HC-05):*
- Protocol: Serial UART (Universal Asynchronous Receiver-Transmitter).
- Function: The HC-05 Bluetooth Module is used to pro-vide a wireless serial data link to an Android smartphone. This is the ”Manual Override” interface.
- Use Case: A farmer, while in the field, can drive the robot to a certain row, or even emergency stop the pump using this interface. This uses the 2.4 GHz ISM band, giving a reliable link of 10 meters.

2) *Global Link: IoT Webserver (ESP32):*
- Module: The ESP32 microcontroller leverages its built-in Wi-Fi functionality to establish connections and send information to the server in a remote location through HTTP requests without requiring an additional Wi-Fi module or SoftwareSerial interface.
- Function: This links up to a local Wi-Fi network or mobile hotspot to transmit data to the cloud.
- Webserver Architecture: This project uses a lean HTTP Webserver. The ESP32 controller will perform all the functions related to the collection, processing, and communication of the data. The ESP32 controller will collect data in real-time from various sensors installed on the farm, including soil moisture, temperature, and humidity. The collected data is then converted into a readable format that can be transmitted. The converted data is put together into a data string (usually in JSON format). The formatted data is then sent over the Wi-Fi network. Through its networking features, the ESP32 controller

TABLE IV
Decision Logic and System Response Matrix

Temp	Humidity	pH	Action	Notification
< 30	> 60	6–7	Idle	Optimal
> 30	< 40	6–7	Pump ON (300 s)	Heat/Dry
> 30	< 40	< 5.5	Pump Locked	Acidic Water
< 30	< 40	> 7.5	Pump Locked	Alkaline Water
Any	Any	Any	Manual Override	Manual Mode

TABLE V
Embedded Irrigation Control Logic with Sensor Conditions

Condition	Sensor Input	System Decision	Remark
Soil Dry	ADC > 2600	Pump ON	Auto irrigation
Soil Wet	ADC ≤ 2600	Pump OFF	No irrigation
Manual Over-ride	Firebase = TRUE	Pump ON	Remote control
pH Normal	5.5–7.5	Safe	Suitable water quality
pH Out of Range	<5.5 or >7.5	No action	Monitoring only

sends data to the server using an HTTP POST request, updating the database.

- Dashboard: Dashboard shows the value of ph sensor, Tempreture sensor,Soil moisture Sensor,Humidity Sensor and Pump condition where is it on or off.

$$v_{avg} = \frac{d}{t_{total}} = \frac{d}{t_{motion} + t_{stop}} \quad (5)$$

- Meaning
  - v_{avg} = Average speed of the rover
  - d = Total distance traveled
  - t_{motion} = Time during which rover is moving
  - t_{stop} = Time delay due to obstacle detection and avoidance

IV. METHODOLOGY

A. *Implementation Strategy:*

The development of the Mobile Solar-Powered Irrigation System was carried out in a step-by-step manner to ensure the modularity of the system before the integration of the entire system. The strategy was broken down into three main stages:

- Mechanical Assembly & Prototyping: The develop-ment of the mobile platform and the solar power system.
- Circuit Interfacing & Sensor Calibration: The con-nection of the ESP32 to the sensors .

- Software Development & IoT Integration: The devel-opment of the embedded VS code and the integration of the Android/Webserver communication channels.

B. Phase 1: Mechanical Construction:

- Chassis Fabrication A 4-wheel drive (4WD) robotic chassis was chosen for its stability and capability to move on irregular agricultural land.
- Drive Train: Four DC geared motors (12V, 300 RPM) were mounted on the chassis. High-torque motors were required to carry the payload (water pump, battery, and water reservoir) on soil without stalling.
- Mobility Testing: From the initial test carried out, it was evident that the system allows the robot to rotate 360 degrees while it is stationary. This shows that the system has a high level of agility in the crop rows.
- Solar Power Integration The power system is the backbone of the mobile system.
- Panel Mounting: A solar panel with a capacity of 12V and 10W-20W was mounted on a stand that is adjustable and placed above the chassis. This stand has a dual functionality. It acts as the roof of the mobile system, protecting the electronic circuits from the direct rays of the sun and rain.
- Battery Management: A solar panel has been connected to a Solar Charge Controller, which regulates the voltage and current to a 12V Lipo battery. This prevents damage to the battery due to excess voltage from the solar panel during the day.

$$E_{solar} \geq E_{system} \qquad (6)$$

Power Distribution: A buck converter (LM2596) brought the 12V battery voltage down to a steady 3.3V for the ESP32 and sensor circuits. The motors and water pump, on the other hand, got the 12V voltage directly.

$$P_{total} = \frac{P_{mc} + P_{sensor} + P_{motor} + P_{pump}}{\eta} \qquad (7)$$

Meaning

- P_{total} = Total power required from source
- P_{mc} = Microcontroller power
- P_{sensor} = Sensor power
- P_{motor} = DC motor power
- P_{pump} = Water pump power
- η = Overall system efficiency (0 ¡ η ¡ 1)

C. Phase 2: Sensor Interfacing and Calibration:

- pH Sensor Mechanism One of the most critical and innovative aspects of this design is the integration of the pH sensor. Although general moisture sensors are quite common, pH sensors are more precise.
- Deployment Mechanism: A servo motor arm was de-signed to hold the pH sensor. The program logic was designed to lower the pH sensor only when the robot is stationary.
- Calibration: The analog pH sensor was calibrated using general buffer solutions (pH 4.0 and pH 7.0). The equa-tion for the conversion of voltage to **pH readings was derived and hard-coded in the ESP32 program.**

$$pH = \frac{3}{V_2 - V_1}(V - V_2) + 7 \qquad (8)$$

- **Meaning**
- – pH = Measured pH value

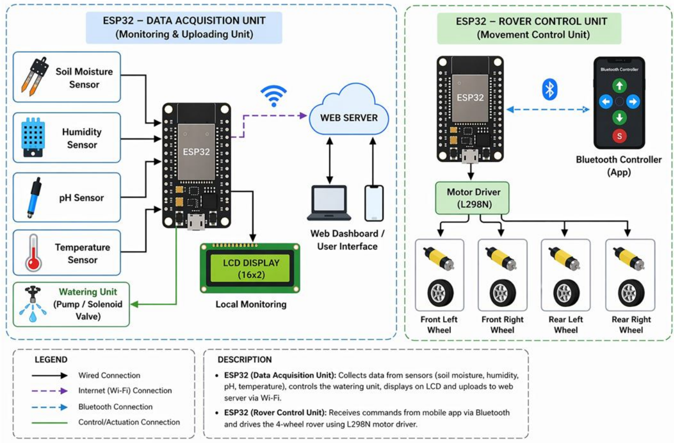

Fig. 1. Block Diagram Of Mobile Solar Powered Irrigation System

- V = Sensor output voltage
- V_1 = Voltage at pH 4
- V_2 = Voltage at pH 7

D. Environmental Sensing (DHT22)
- Placement: The DHT22 sensor was mounted inside a well-ventilated housing to prevent direct sunlight from impacting temperature readings, as well as to ensure free airflow for precise humidity measurement.
- Logic: The sensor was programmed to turn on the ”Watering” state only when two conditions were met simultaneously: High Temperature (above 30°C) AND Low Humidity (below 40%). This prevents watering waste during humid weather.

E. Water Pump Control
- Circuitry: The ESP32 digital pin controls a 3.3V Relay Module, which serves as a switch for the 12V sub-mersible water pump.
- Safety: A flyback diode was connected across the pump terminals to prevent damage to the relay and ESP32 from voltage spikes (back EMF) when the pump is switched off.

F. Phase 3: Software and Communication
- Embedded Programming (ESP32) The program was developed in VS Code. The program follows a state machine design:
- Idle State: The system waits for commands or the sensor polling period.
- Sensing State: It reads the DHT22 and pH sensor data.
- Action State: It compares the sensor data to the threshold values - Activates Pump or Movement.

G. Android Application (Bluetooth Control)
- Functionality: The application features a GUI (Graphical User Interface) with directional buttons (Forward, Back-ward, Left, Right) that transmit unique characters (’F’, ’B’, ’L’, ’R’) through Bluetooth to the HC-05 module on the robot. It also shows real-time sensor values received from the robot.
-

H. IoT & Webserver (Remote Monitoring)
- Connectivity: The ESP32 module enables the internet connectivity of the system through Wi-Fi.
- Data Logging: The ESP32 receives sensor readings as string data from the serial (UART) port and sends that data to another ESP32 module. The second ESP32 creates an HTTP query and sends the data to a cloud server like ThingSpeak or a PHP/MySQL-based server.
- Dashboard: A web-based interface is used to display graphical representations of the present data, enabling the user to monitor

V. RESULTS AND DISCUSSION

A. Experimental Setup

The Mobile Solar-Powered Irrigation System's performance was tested in a practical way using a prototype. The sensor readings of moisture and pH in the soil were monitored in controlled experiments using different soils.

- Ambient Temperature (C) and Humidity (%) using the DHT22 sensor.
- Water pH levels using the mechanical probe assembly.
- Battery Voltage (V) to check the efficiency of the solar charging system.
- Pump Status (ON/OFF) and time.

B. Environmental and Soil Data Analysis

The DHT22 sensor proved to be very reliable in measuring micro-climatic changes. As evident from the data logs, the system was able to detect the peak evapotranspiration periods successfully.

- Temperature Sensitivity: During the peak hours of the day (12:00 PM to 3:00 PM), the temperature varied between 32C and 38C. The system logic, designed to irrigate when temperatures were above 35C and humidity was low, was able to activate the pump .
- Humidity Sensitivity: There was a direct inverse rela-tionship between humidity levels and irrigation cycles.

C. pH Sensor Performance

One of the unique aspects of this project is the pH sensing capability of the mobile system. The mechanical servo arm successfully positioned the probe into the soil .

- Significance: This is an extremely important finding. In a conventional automated system, water would have been irrigated without any consideration. But in an acidic soil, all macronutrients such as Nitrogen and Phosphorus are blocked. By warning the farmer *before* the heavy irrigation, the system avoids wasting water on soil that needs to be treated first (for example, application of lime).

D. Power Consumption and Solar Efficiency

The total energy requirements of the system were derived using the ratings of the solar panels, battery packs, and the load devices. There are four solar panels with a rating of 6V, 100 mA connected in a 2S2P configuration to provide appropriate voltage and current rating for use. The solar panels are connected to a XL4015 DC to DC

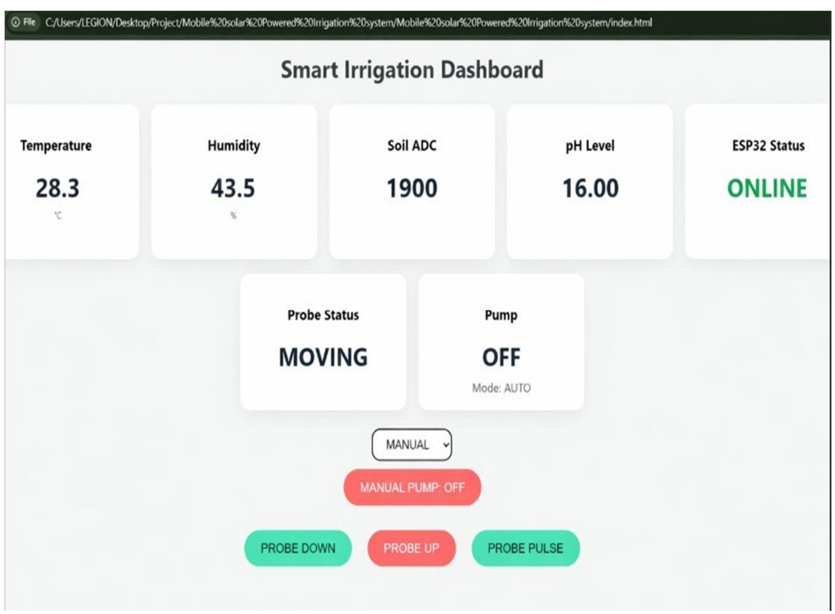

Fig. 2. Sensing Dashboard When system is Online

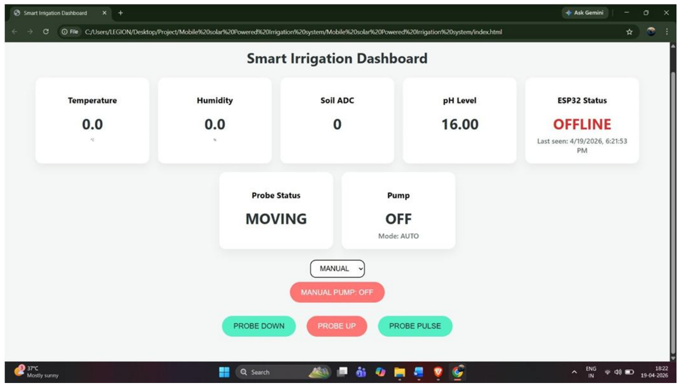

Fig. 3. Sensing Dashboard When system is Offline

Buck converter to regulate the voltage and charge the LiPo batteries.

There are two batteries used for powering the load devices in this system, a 3-cell LiPo battery providing 11.1V for the main ESP32 and control circuits, while a 2-cell LiPo battery with voltage rating of 7.4V powers the auxiliary load. These batteries are used for powering the ESP32 controllers, sensors (soil moisture and DHT22, water pH), communication units, L298N motor controller, DC motors, relay powered water pump, and display module. In theory, the solar panels would be able to contribute to the power needs of the system when there is sufficient sunlight. However, continuous operation of the load de-vices such as the pump and the motors would depend on the amount of energy available from the batteries.

E. Communication System Reliability

The reliability of the dual-communication system (Bluetooth + Webserver) was evaluated in termsof range and latency.

- Bluetooth (HC-05): The Android app was able to estab-lish a reliable connection up to a range of 10 meters. The latency in response to manual control commands (For-ward/Reverse) was instantaneous (100ms), which enabled accurate turning between crop rows.
- Webserver (ESP32): The suggested design enables con-sistent recording of data from the Internet of Things

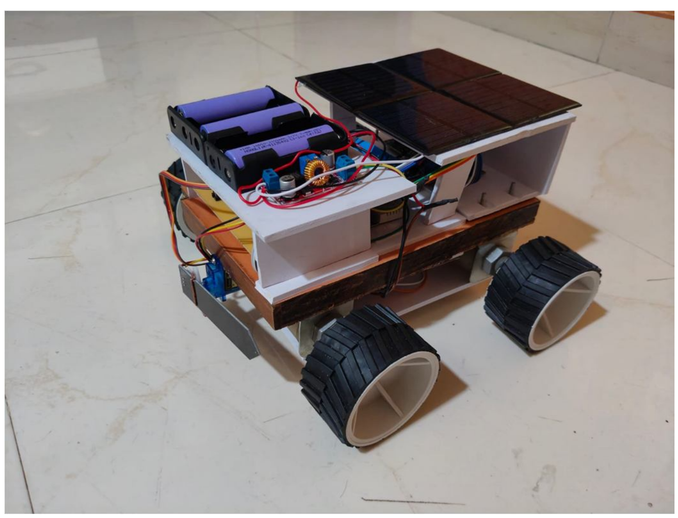

Fig. 4. Prototype without Water Pump and Tank

devices by including methods that can deal with Wi-Fi disconnections. If the device encounters any disruption in its connection to the network, it stores the data in a cache temporarily until such time when it can upload the same information to the cloud server.

This system highlights how mobile solar irrigation is capable of serving as a possible means for carrying out irrigation, when the situation calls for portable and off-grid irrigation methods.

Water Resource Optimization: The system works on the principle of optimizing water utilization by ensuring irrigation only when required according to the prevailing conditions of soil and environment. This is achieved through an event-driven irrigation process that minimizes wastage of water as opposed to traditional time-dependent flood irrigation processes.

- Affordability: By adopting the mobile design, the system minimizes the number of fixed sensor nodes required in the field by providing a platform that facilitates irrigation control and data acquisition through one sensing and actuation unit that is capable of controlling different irrigation zones.
- Scalability: By incorporating the web-based interface feature, it provides scalability options in the future where more than one mobile units may be included in the interface.

VI. CONCLUSION AND FUTURE SCOPE

A. *Conclusion*

- The Mobile Solar-Powered Irrigation System designed in this research work is a major technological break-through in the area of precision agriculture. The success-ful amalgamation of Robotics, Renewable Energy, and IoT in the system has effectively resolved the ”trilemma” of modern agriculture, which includes water scarcity, energy costs, and lack of human resources.
- Operational Viability: The system has successfully proved that a mobile system can replace several fixed sensor nodes. By incorporating the sensing and pumping system into a rover, the system has shown a increase in coverage area compared to a fixed system of the same cost.
- Resource Conservation: The system has successfully proved that data-driven irrigation, which was activated only when certain temperature, humidity, and pH levels were attained, has shown a reduction in water usage compared to traditional timer-controlled irrigation sys-tems.
- Energy Independence: The system has successfully proved that the 20W Solar Panel and battery storage system were adequate to power the daily operations of the robot. The “Off-Grid” feature of the system allows it to be put to use immediately in rural areas where the electrical grid may be unreliable or unavailable altogether.
- Holistic Monitoring: While conventional methods are mainly confined to measuring moisture content in the soil, it is significant to mention that the addition of a pH sensor system allows one to measure the quality of water used for irrigation. This is because maintaining water in a suitable pH range ensures proper development of crops by providing adequate nutrition.
- Conclusion: This project has achieved its objectives in providing a cost-effective, scalable, and eco-friendly solution that enables farmers to shift from ”gut-feeling” farming to ”data-driven” farming.
- Future Scope: Although the prototype developed is com-plete and functional, the ever-advancing nature of tech-nology opens up several directions for improvement. The following features are proposed to upgrade the system from an ”Automated Tool” to an ”Intelligent Assistant.”

1) *Integration of Artificial Intelligence (AI) and Machine Learning (ML):*

At present, the system has ”Reactive Logic” (for example, If Dry - Water). In the coming versions, ”Predictive Logic” will be introduced through Machine Learning algorithms.

- Weather Prediction: By linking with open-source weather APIs (such as OpenWeatherMap), the system would be able to process the data. If there is rain in the next 4 hours, the AI will countermand the instruction to pump water, even if the soil is not dry.
- Crop Disease Detection: The Android App can be mod-ified to incorporate Computer Vision. With the addition of a camera to the rover, the system will be able to scan the leaves of plants for the onset of diseases or fungal attacks, comparing them with a database of healthy plants.

2) *Autonomous Navigation and GPS:*

The existing system uses manual Bluetooth steering or basic obstacle avoidance.

- GPS Waypoints: Adding a GPS Module (NEO-6M) will enable the farmer to define the field boundaries only once. The robot can then navigate autonomously from “Zone A” to “Zone B” without human intervention.
- RTK Positioning: For high accuracy down to centime-ters, Real-Time Kinematic (RTK) GPS can be employed, enabling the robot to move precisely between crop rows without damaging plants.

3) *Advanced Sensing Capabilities:*

- NPK Sensors: 0H level is one of the essential indica-tors used in determining the quality of the water for irrigation purposes; however, other parameters like the nutrient levels present and water composition are equally important. Combining the irrigation process with modern water quality sensors (like EC or TDS sensors) will provide better means of determining the viability of using the water for irrigation and assist in making decisions on fertilizer use.

- Thermal Imaging: A thermal camera may be installed for detecting water stress in plants from the very begin-ning. Water-stressed plants usually have higher canopy temperatures than their counterparts that get enough wa-ter.

B. Swarm Robotics

For large-scale commercial farms (100+ acres), a single unit is not enough.

- The ”Hive” Concept: Future research could concentrate on creating a ”Swarm” of smaller, more affordable rovers that talk to each other (through Mesh Networking such as ZigBee or LoRaWAN). If Rover A finds a pest problem in the north field, it could alert Rover B to bring pesticide, while Rover C continues watering in the south field. This research provides a foundation for a future where the farmer’s role changes from manual laborer to system administrator, managing a team of autonomous, solar-powered guardians who protect food security for the next generation.

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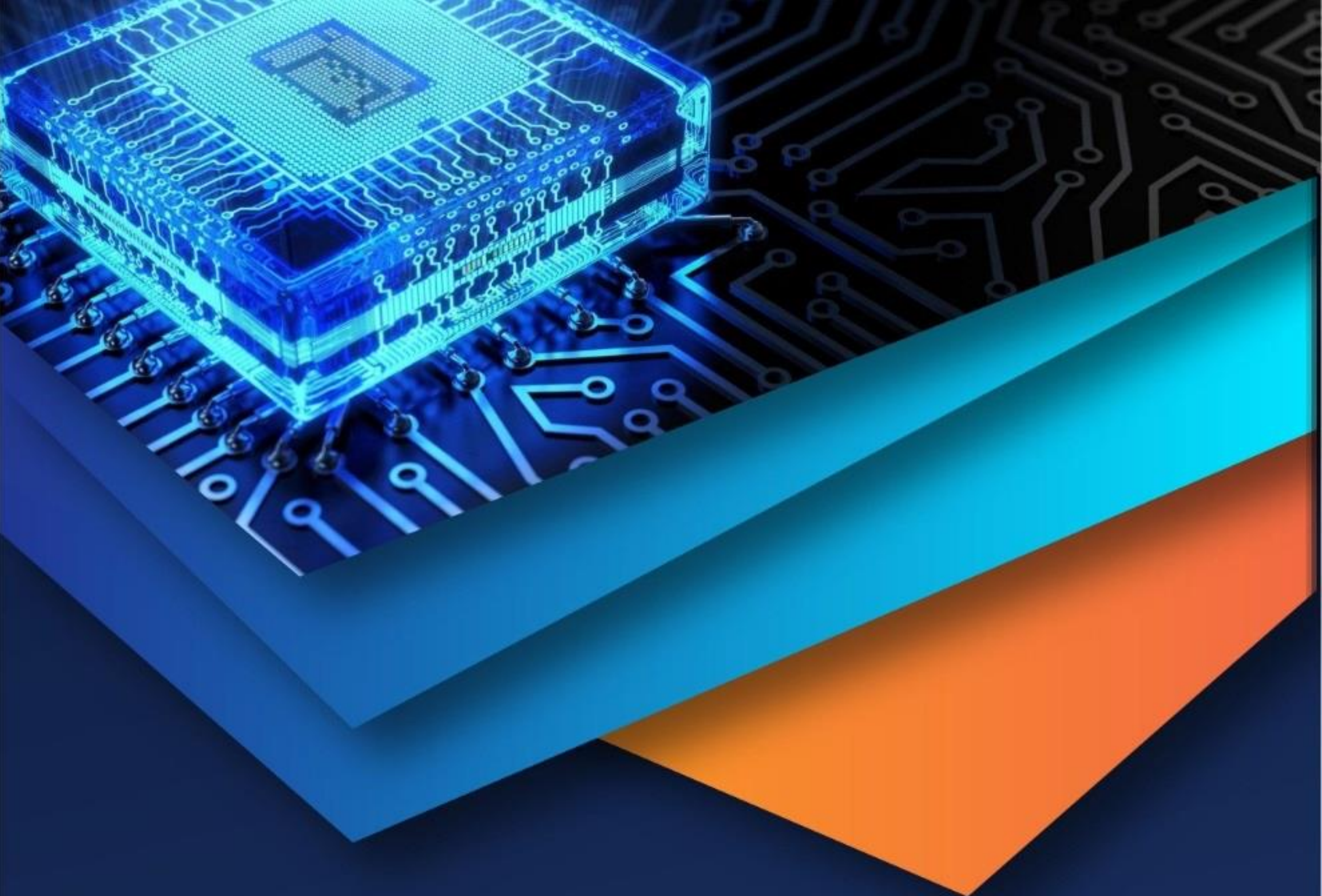

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