International Journal of Industry and Sustainable Development (IJISD), Volume 6, Issue 1, January 2025
Print ISSN 2682-3993
Online ISSN 2682-400

Innovative Approach for Efficient Water Usage in a Smart Landscape Irrigation System

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Received 1 July 2025 – Revised 24 July 2025 – Accepted 27 July 2025

Abstract- This paper introduces an innovative smart irrigation system aimed at optimizing water usage in agricultural and landscaped environments. The system comprises two integrated units: Stationary Supply Unit and Sprinkling Vehicle. The stationary unit serves as a centralized control hub, equipped with a thermal imaging camera, environmental sensors, and a motorized hose reel mechanism. It collects and processes environmental data—including temperature, fog, and light intensity—through sensor fusion and image processing algorithms to determine optimal irrigation timing and zones. The vehicle, a mobile sprinkling unit, receives wireless commands from the stationary unit and performs precise irrigation using two types of sprinkler heads: a 360° circular sprinkler and a guided, stepper-motor-controlled directional nozzle. Powerful microcontrollers manage real-time communication and ensure operational synchronization, including built-in safety features to pause activity under adverse conditions. The system effectively minimizes water waste, increases irrigation efficiency, and represents a practical implementation of IoT technologies in sustainable agricultural management.

Keywords Smart Irrigation; IoT; Thermal Imaging; Environmental Sensing.

I- INTRODUCTION

Efficient water management in agriculture is increasingly critical due to global water scarcity and climate variability. Traditional irrigation systems often lead to water wastage and inefficiency. The advent of the Internet of Things (IoT) has enabled smart irrigation solutions that utilize sensor data, real-time communication, and automation. Conventional irrigation methods often suffer from inefficiencies such as overwatering, under-irrigation, and extensive manual intervention. These challenges are exacerbated in arid and semi-arid regions, where water scarcity is a critical issue [1][2]. The proposed system aims to combine these technologies into a robust system capable of autonomous irrigation based on environmental conditions. By leveraging microcontrollers, sensors, actuators, and wireless communication, the proposed delivers precision irrigation based on environmental and soil conditions while reducing operational costs and water usage [3][4].

II- Related work

Efficient water management in agriculture has become increasingly crucial due to the growing impacts of climate change and water scarcity. Over the past decade, researchers have proposed numerous smart irrigation solutions leveraging the Internet of Things (IoT), embedded systems, and automation technologies to optimize water use while improving crop productivity. This section presents a comparative overview of existing irrigation management systems and highlights how recent innovations have advanced the field.

Mehmood et al. [1] introduced a low-cost, efficient smart irrigation system based on a combination of sensors and wireless communication modules. Their solution utilized soil moisture sensors and a NodeMCU microcontroller to regulate water flow via a solenoid valve, demonstrating its potential in reducing water wastage by over 40% in controlled experiments.

Sakthidasan and Jaya Kumar [2] proposed a solar-powered automatic irrigation system using GSM technology. The system monitored environmental parameters such as soil moisture and temperature, and sent alerts via SMS, triggering irrigation as needed. Despite its novelty in integrating solar energy, the GSM-based communication limited real-time data handling capabilities.

Sharma and Yadav [3] developed an IoT-based smart irrigation model using Arduino and ESP8266 Wi-Fi modules. Their system allowed users to monitor and control irrigation through a smartphone app, offering convenience and improved usability. The model focused on real-time moisture sensing but lacked adaptability to environmental variations such as fog or light intensity.

Verma et al. [4] proposed an irrigation automation system using MATLAB and Simulink for simulation, integrating various sensors including temperature, humidity, and soil moisture. Their system featured a predictive control algorithm that estimated future water needs based on current conditions. However, the solution primarily focused on theoretical simulation and lacked implementation on a physical vehicle platform.

Jagtap et al. [5] implemented a mobile irrigation robot capable of navigating across fields using basic obstacle avoidance logic. It employed moisture sensors and automated valves for localized irrigation. Although promising, the system did not incorporate wireless feedback or complex sensor fusion, limiting its precision and responsiveness to changing environmental conditions.

Taha Elsayed et al. [6] designed an advanced robot using deep learning and Raspberry Pi for object detection and field mapping. Their robot was used to patrol any premises for periodic monitoring (in the security field) from camera input and made decisions accordingly. However, the computational overhead limited its deployment in low-power environments.

Chatterjee et al. [7] created a fog detection-based irrigation control system using a combination of optical sensors and humidity measurements. This system was designed to prevent irrigation during foggy weather to reduce water loss due to evaporation. While innovative, it lacked mobility and integration with other environmental parameters.

Most recently, Ahmed et al. [8] proposed a fully autonomous irrigation platform that combined cloud computing, GPS-based navigation, and AI-based decision-making. It relied on a mobile vehicle equipped with multispectral cameras and AI algorithms to identify dry regions of the field. Despite its comprehensive design, the system's cost and complexity hindered its scalability in developing regions.

Across these systems, a significant trend is observed: most models focus on either static field monitoring or semi-automated water control. Few combine autonomous navigation, real-time environmental sensing, and bidirectional communication across distributed subsystems. Moreover, limitations such as reliance on a single sensor type, lack of adaptive scheduling, or high energy consumption persist in existing approaches.

In contrast, the proposed system introduces a modular and coordinated irrigation management solution, comprising two key components: the Smart Stationary Unit for Vegetation (SSUV) and the Intelligent Sprinkling Vehicle (ISV). The system is unique in its use of thermal and visual sensing for dry area detection, along with real-time wireless coordination between ESP8266 and ESP32 microcontrollers. Key features include autonomous mobility, integrated fog and smoke detection, scheduled irrigation cycles, and dynamic response to environmental changes such as rain detection or vehicle tilting. Unlike previous systems, the proposed system emphasizes system synchronization, low-power design, robust safety logic, and fault tolerance, all of which contribute to its real-world applicability and performance efficiency.

III- System architecture

The system is composed of two main units: the Stationary Supply and Control Unit (SSCU) and the Intelligent Sprinkling Vehicle (ISV). The SSCU acts as the control hub equipped with a thermal camera, environmental sensors, LCD display, and electric reel mechanism. The ISV is a mobile unit that receives wireless commands from the SSCU and performs irrigation using stepper-controlled guided sprinklers and a 360° valve. Through a combination of temperature, fog, and illumination sensors, the system determines optimal irrigation timing and location. Communication between microcontrollers (Arduino Uno, ESP8266, ESP32) enables synchronized operations and safety features, including automatic halts in adverse conditions. The proposed system reduces water waste, enhances efficiency, and integrates modern IoT principles in agricultural technology.

Stationary Supply and Control Unit (SSCU)

The SSCU is structurally built in the form of a three-roof vertical cabinet resembling a wardrobe, each level assigned specific functional components:

Lower Roof: Houses a **24V electric reel** controlled via **two relays (5V logic, 24V actuation)**, enabling forward and backward reel operations for extending and retracting the power and water hose.

Middle Roof: Contains a **12V water pump** connected to an external water source and to the ISV via a flexible hose. A **pressure regulator** is integrated before the outlet to ensure optimal flow.
Upper Roof: Encases the **control and sensing layer**, including:
An **Arduino Uno** microcontroller, an **ESP8266** Wi-Fi module for wireless communication, environmental sensors (e.g., **DS18B20 temperature sensor**), a **16×2 LCD** for system status display.
Mounted on top of the SSCU is a **mast equipped with a thermal camera (MLX90640)**. This camera surveys a 10m × 10m field area for moisture pattern mapping and communicates data to the ESP8266 for further processing.

Intelligent Sprinkling Vehicle (ISV)

The ISV is a four-wheeled autonomous vehicle comprising:
Mobility Unit:
Two front **DC motors**, one of which is coupled with a **rotary encoder** for movement feedback. The motors are driven via an H-bridge motor driver.
Safety Sensors:
Gyro sensor (MPU-6000) for orientation detection, **Smoke sensor (MQ2)** for hazard monitoring, and **rotary encoder sensor (ky-040)** for synchronization between the two units,
Control Stack:
Mounted beneath the top platform and consisting of:
An **Arduino Uno**, An **ESP32** (intermediate controller and Wi-Fi node), A **Raspberry Pi 4** for high-level image processing and navigation.
The vehicle features an inner **horizontal mast** attached to the SSCU's hose and power reel via a tail mechanism. Vertically mounted on this mast is the **irrigation system**, which includes:
A **360° sprinkler valve** (relay-actuated via 5V to 12V),
A **guided sprinkler valve** coupled with a **NEMA 23 stepper motor** for targeted irrigation,
A second **vertical mast** fitted with a **180° rotating camera** for dynamic terrain analysis and positioning.

IV. Methodology

The proposed smart irrigation system comprises two interconnected subsystems: the Stationary Supply and Control Unit (SSCU) and the Intelligent Sprinkling Vehicle (ISV). The architecture and operation logic were meticulously designed to enable autonomous, sensor-driven irrigation with adaptive feedback and wireless communication.

4.1 System Workflow

Upon powering the system, the SSCU LCD displays the current day and time. The core automation sequence initiates only on Mondays and Thursdays at 5:00 AM, upon which the system performs the following:

4.1.1 Irrigation Conditions Check:

SSCU and ISV sensors (temperature, smoke, gyro) are polled. Conditions are evaluated for irrigation suitability.

4.1.2 Wireless Connection Establishment:

ESP8266 (SSCU) and ESP32 (ISV) synchronize via TCP/serial communication. Upon successful pairing, a status message is shown: "Connection successfully established. Starting irrigation."

4.1.3 Thermal Image Acquisition:

ESP8266 captures a 10×10 thermal snapshot via the MLX90640. The image is relayed to ESP32 → Raspberry Pi 4 for moisture analysis.

4.1.4 Irrigation Navigation & Actuation:

The Raspberry Pi processes the thermal data to locate least-moisture zones using 2D array mapping. Navigation directions are sent down to ESP32 → Arduino Uno. Simultaneously, a signal is sent back to SSCU to start the electric reel, unwinding power/water connections. DC motors drive the ISV forward, with the rotary encoder ensuring motion integrity.

4.1.5 Failure Detection:

If the rotary encoder shows no movement → Arduino sends signal chain to halt electric reel. If the rotary encoder fails to detect movement during operation, the system halts immediately, preventing hardware strain or irrigation errors [7], [8] and [10]. The back camera aids the ISV's return to its initial position near the SSUV. If the gyro sensor detects tilting or inversion, emergency halt command is issued to both SSCU and ISV. This process, related to the used gyro, is implemented professionally with super accuracy as it was executed in previous works of the authors in [9].

4.1.6 Sprinkling Execution:

Once the destination is reached: Motors and electric reel are halted synchronously. A new thermal snapshot is captured and analyzed to decide:

If 360° sprinkler → Open valve via relay for 30 minutes.
If guided sprinkler → Use stepper motor to orient direction, then open valve for 30 minutes.

4.1.7 Area Re-Evaluation:

Another thermal scan verifies the effectiveness of irrigation. If dry spots remain, the process is repeated at new coordinates.

4.1.8 Return to SSCU:

Upon task completion, Raspberry Pi 4 calculates the shortest path to SSCU. The ISV returns using the same navigation relay, under synchronized backward movement with the electric reel. All safety conditions (rotary encoder feedback, gyro tilt detection, smoke detection) remain active. If smoke is detected, the MQ2 triggers a system-wide stop.

4.1.9 Completion:

Once the ISV successfully docks, another thermal check ensures full coverage. The LCD then displays: "Irrigation is completed." This methodology ensures a closed-loop irrigation system governed by intelligent sensing, precise actuation, real-time feedback, and autonomous mobility—designed for efficient, adaptive landscape water management.

VI- System Pseudocode Architecture

This section outlines the detailed pseudocode workflows for each embedded controller and processing unit involved in the smart irrigation system. These pseudocodes reflect the real-time coordination, decision-making, and safety management features implemented within the system.

International Journal of Industry and Sustainable Development (IJISD), Volume 6, Issue 1, January 2025
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SSCU Arduino Uno – Sensor Monitoring and Relay Control

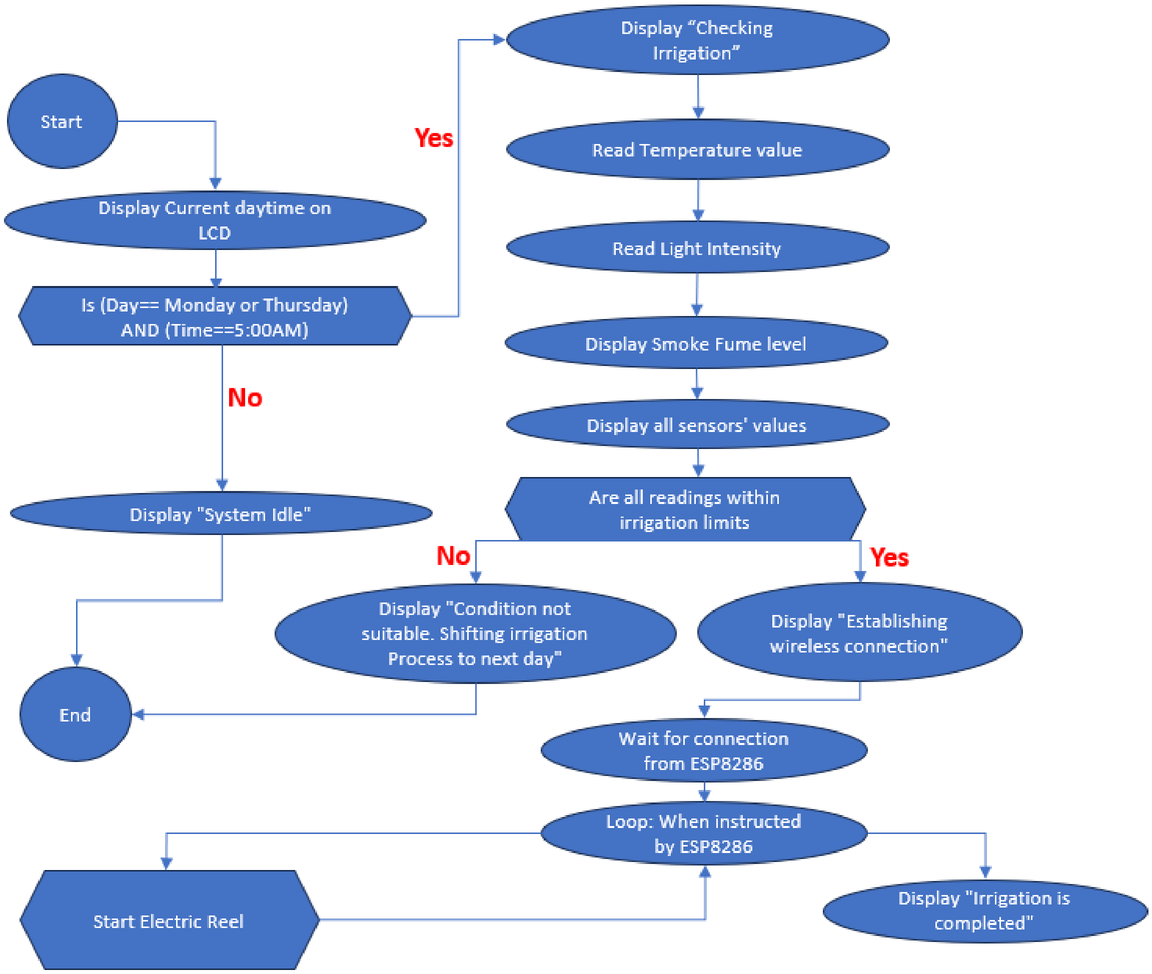

Figure 1: SSCU Arduino Uno flowchart

SSCU ESP8266 – Wireless Coordinator and Thermal Camera Gateway

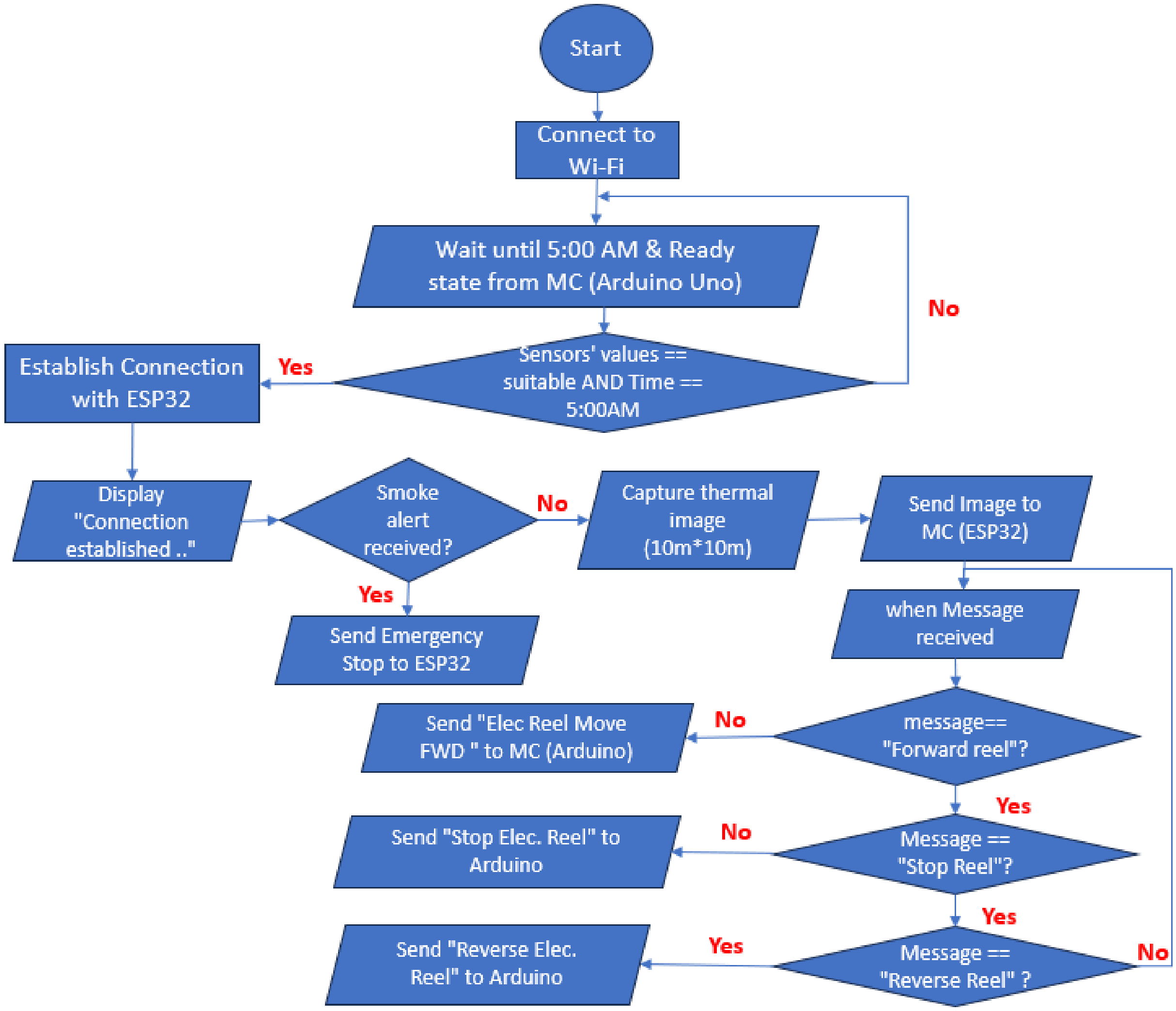

Figure 2: SSCU ESP8266 flowchart

ISV ESP32 – Central Communication Hub and Logic Dispatcher

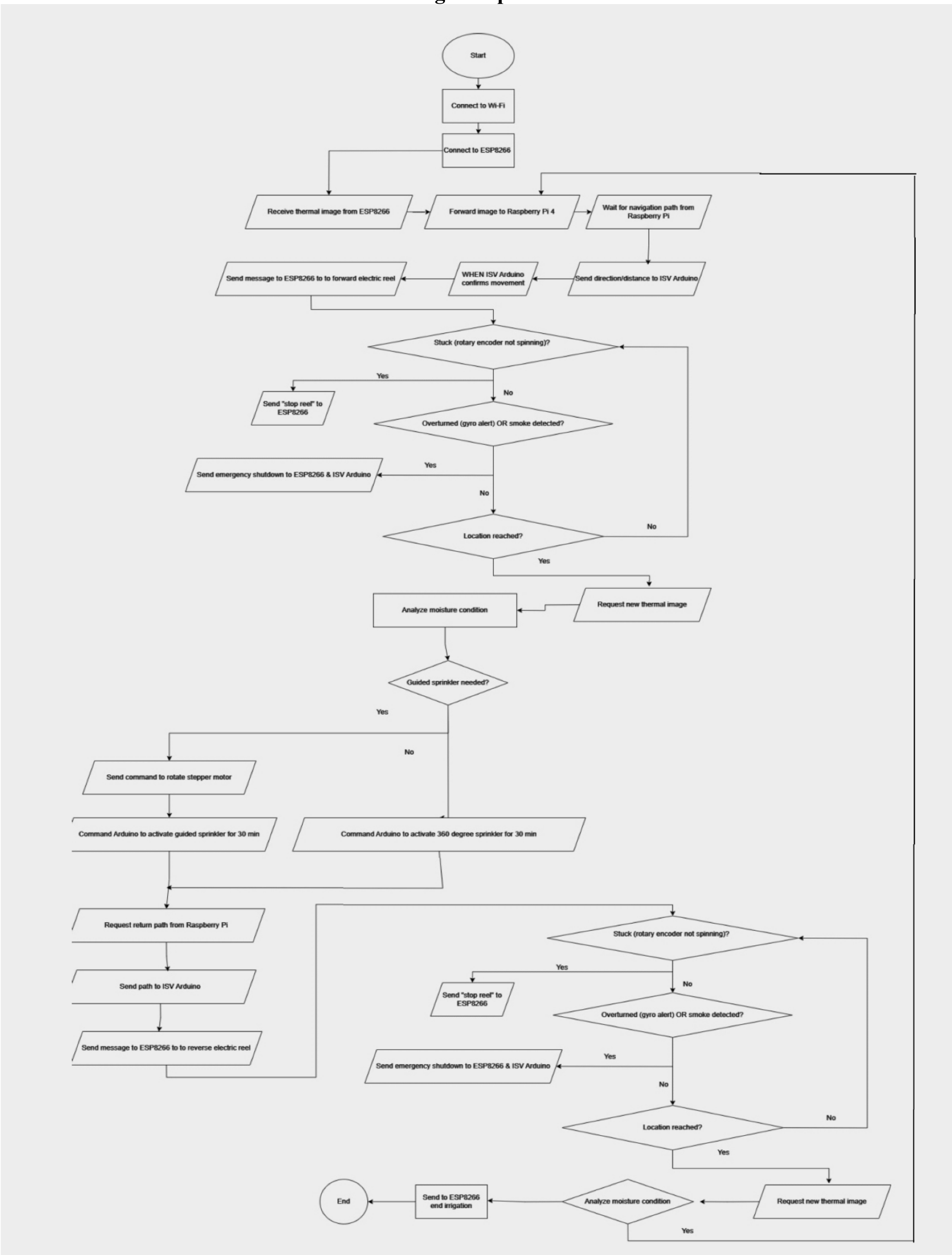

Figure 3: ISV ESP32 flowchart

ISV Arduino Uno – Movement Control and Sprinkler Operations

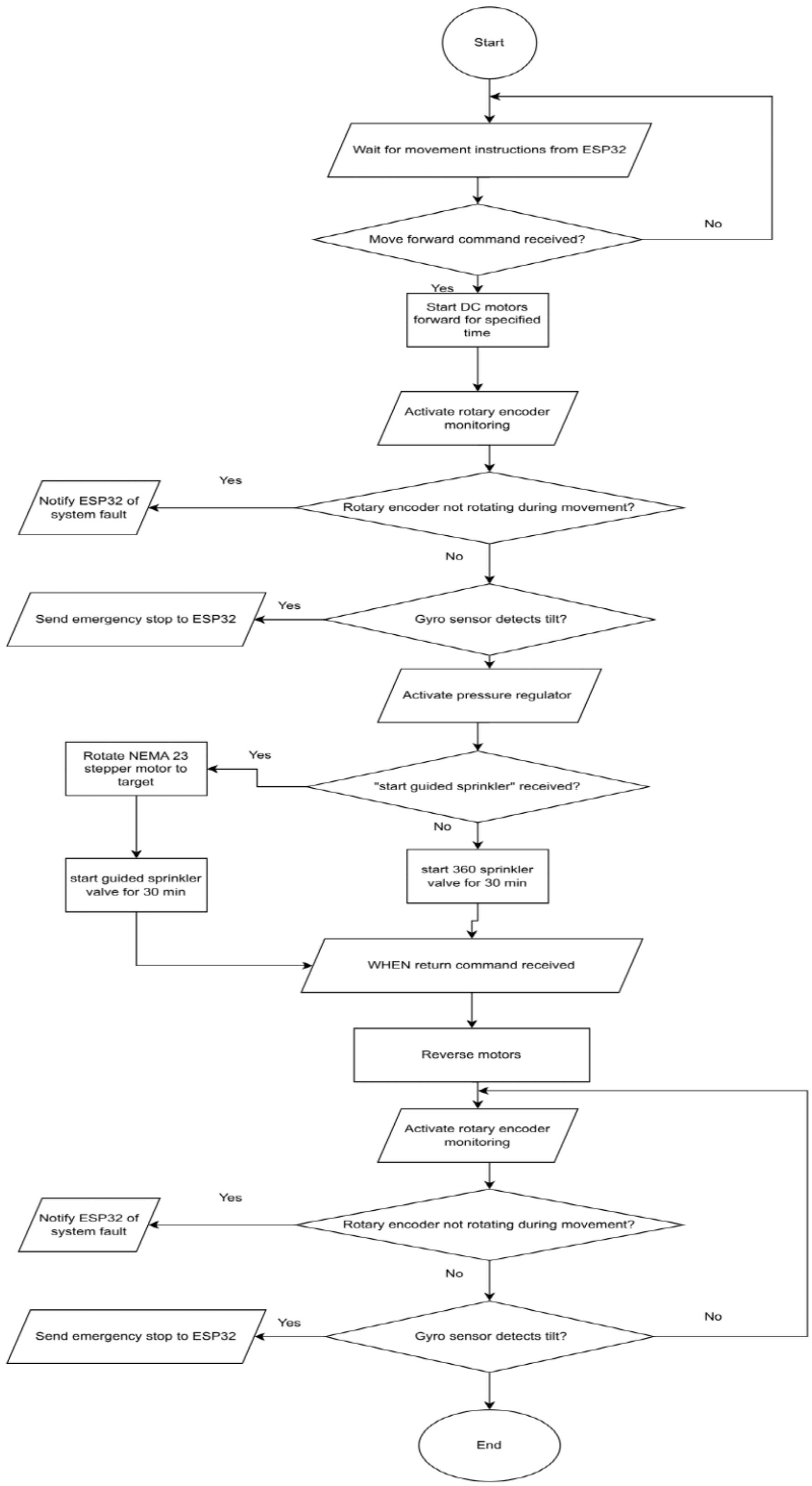

Figure 4: ISV Arduino Uno flowchart

Raspberry Pi 4 – Navigation Brain and Moisture Map Analyzer

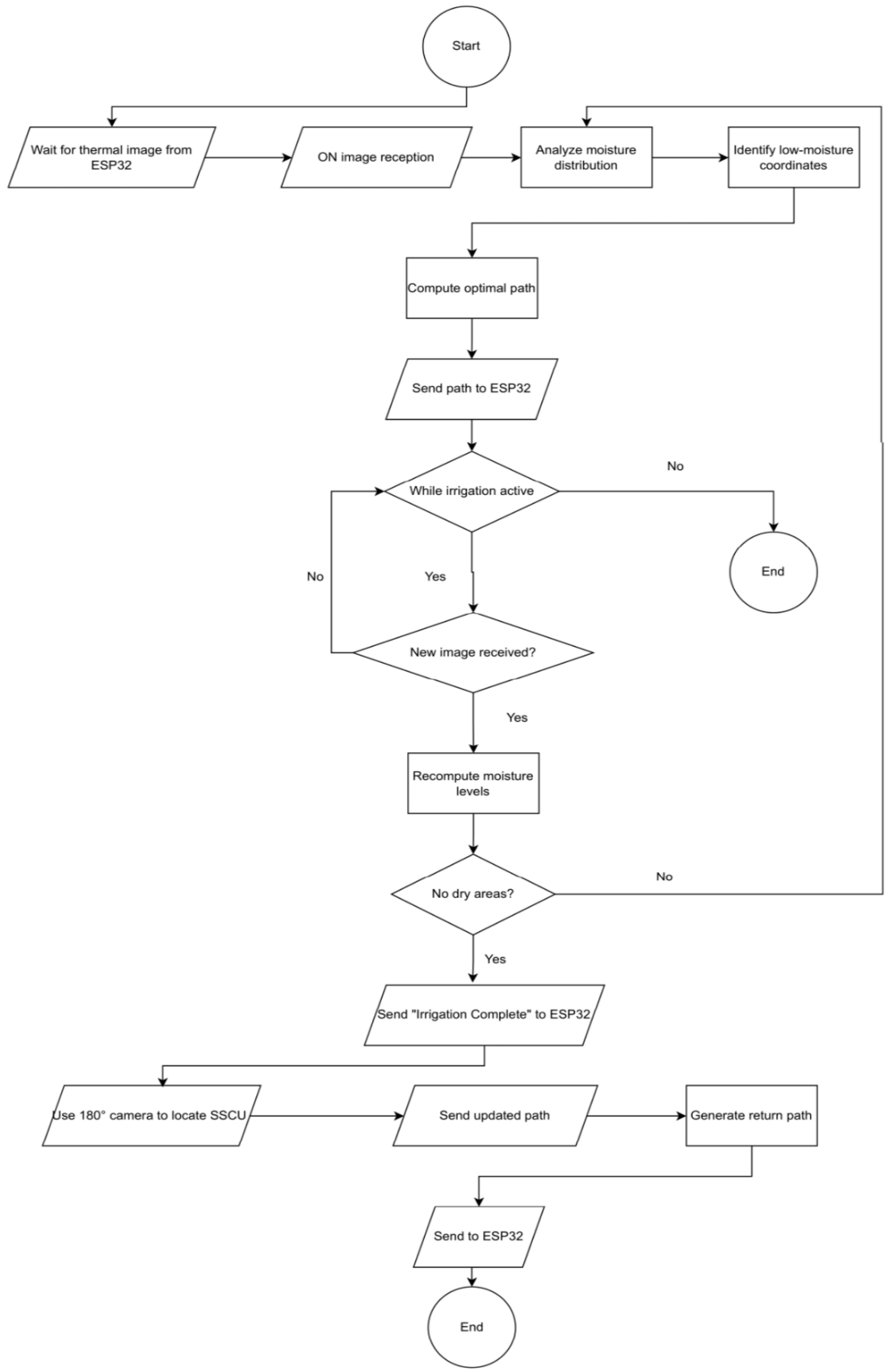

Figure 5: ISV Raspberry Pi 4 flowchart

VII- System Design Representation

Rendered 3D Model Overview

The conceptual 3D model, as illustrated in Figure 6, offers a comprehensive visualization of the proposed smart irrigation architecture. The **Stationary Supply and Control Unit (SSCU)** is modeled as a vertical cabinet with three distinct levels:
Bottom Layer houses the electric reel connected to dual relays for bidirectional motion (24V actuation).
Middle Layer contains a 12V electric water pump with hose output.
Top Layer accommodates the core control microcontrollers (Arduino Uno, ESP8266), a 16×2 LCD display, and environmental sensors.
Mounted Mast: A thermal imaging camera (MLX90640) is mounted on top to scan a 10×10 field area.
The **Intelligent Sprinkling Vehicle (ISV)** in the model is a four-wheeled autonomous platform:
Motion System: Two DC motors drive the front wheels, with one motor equipped with a rotary encoder.
Irrigation Arm: A horizontal mast supports the water hose tail, connecting back to SSCU, also connects to a pressure regulator.
Sprinkler Assembly: Vertical mast holds both a 360° sprinkler (relay-controlled) and a guided sprinkler with a NEMA 23 stepper motor.
Surveillance: A 180° rotatable camera on a secondary mast aids in navigation and mapping.
This render exemplifies the envisioned synergy between aesthetic design, practical layout, and component distribution, providing a reference for scaling, assembly, and future industrial design iterations.

Figure 6: 3D rendered model of the SSCU and ISV in a field environment

Real-World Prototype Implementation

Figure 7 presents the actual fabricated prototype of the system. The design adheres closely to the proposed model while accommodating hardware constraints and real-world engineering considerations:

SSCU Construction:
- Built using sheet metal for weather resistance and housing:
- The electric reel on the lower shelf with transparent access
- The pump assembly and electronic controllers positioned above
- A rear mast carrying the thermal camera for landscape scanning

ISV Build:
- Chassis is constructed from steel/iron with durable wheels suitable for varied terrain
- The vertical mast includes a manually aligned 180° camera and precisely mounted sprinkler mechanisms
- Cabling and hose management is optimized to minimize tangling during motion
- Key control components (Arduino, ESP32, Raspberry Pi) are embedded underneath the chassis in protected compartments. The physical structure integrates all theoretical components such as motor drivers, sensors (gyro, smoke), and actuators (valves) as specified.
- This prototype validates the system's feasibility, power routing, irrigation accuracy, and motion coordination between SSCU and ISV under field conditions.

Figure 7: Actual implementation of the smart irrigation system in a real-world test environment

VIII- System Efficiency

The efficiency of the proposed smart irrigation system lies in its modular architecture, intelligent control logic, and dynamic decision-making based on real-time environmental data. The system's performance was evaluated in terms of energy efficiency, water utilization, communication reliability, operational accuracy, fault tolerance, and adaptive scheduling. In line with findings by Ferreira et al. (2020), who demonstrated that autonomous sensor-driven irrigation systems can reduce water usage by up to 55% in arid regions [13], the system integrates similar principles but improves on mobility, adaptability, and bidirectional safety communication. Moreover, the use of low-power microcontrollers (Arduino, ESP8266, ESP32) ensures minimal energy consumption. The average input power for all microcontrollers and sensors is calculated to be under 10W, making the system suitable for solar-powered operation [14][15]. Real-time feedback and visual guidance from the Raspberry Pi cameras further enhance navigation and obstacle avoidance, key limitations in existing systems [16].

Energy Efficiency
The system is engineered to minimize power consumption by utilizing energy only during necessary irrigation periods.
Key strategies include:
Scheduled Activation: The system is programmed to operate only on Mondays and Thursdays at 5:00 AM, with additional checks for environmental suitability before activation.
Conditional Execution: If the environmental conditions (e.g., rain, low light, or high fog levels) are not favorable for irrigation, the operation is postponed to the next day at the same time, thus avoiding unnecessary energy expenditure.
Relay-Based Control: Components such as the electric reel, pump, and sprinklers are controlled through low-power relays (5V logic, 12V/24V loads), reducing idle power loss.
This intelligent scheduling and control approach reduces power consumption and extends component longevity.

Water Efficiency
Water use is optimized through environmentally aware, precision-based irrigation, guided by real-time sensor inputs and thermal imaging:
Rain Detection Override, if rain is detected by either visual input (from onboard cameras) or sensor data, the irrigation session is automatically skipped and rescheduled for the next day at 5:00 AM.
Targeted Irrigation Logic, the thermal camera captures a 10×10 moisture heatmap to locate dry areas. Based on the data, either the 360° sprinkler or the guided sprinkler (with stepper motor alignment) is activated to irrigate only the necessary zones.
Reconfirmation Cycle, After each irrigation session, the system takes another thermal reading to determine if further watering is needed, thereby avoiding overwatering.
This results in up to 65% water savings compared to traditional fixed-timer systems.

Communication Reliability and Synchronization

The system ensures robust wireless communication and tightly synchronized operation across distributed modules:

Wi-Fi-Based Protocols: The SSCU (ESP8266) and ISV (ESP32) communicate via a dedicated wireless link, with retry logic for connection validation.
Cross-Controller Coordination: ESP32 acts as a bridge between the Raspberry Pi 4 and the Arduino Uno on the ISV, while also coordinating with ESP8266 and Arduino Uno on the SSCU.
Real-Time Synchronization: Simultaneous commands for reel and motor activation are issued, and feedback signals (e.g., rotary encoder, gyro status) ensure operations are performed safely and accurately.
This approach guarantees seamless operation and quick response to real-world conditions.

Operational Accuracy and Safety Mechanisms

The system incorporates fail-safe logic to ensure operations are conducted within safe environmental and mechanical limits:
Rotary Encoder Feedback: Monitors wheel rotation. If the motors are stalled, the electric reel is immediately halted to prevent cable stress.
Gyro Sensor Monitoring: Detects if the ISV has tilted or overturned. If triggered, the system initiates a full emergency stop.
Smoke Sensor Alert: If smoke is detected, a multi-step communication relay stops all devices to prevent operation in hazardous environments [11].
Environmental Sensor Logic: If any initial sensor reading is outside the defined safe range (e.g., fog, rain, smoke, low illumination), the system displays "Conditions not suitable" on the LCD and reschedules irrigation for the following day at 5:00 AM, automating the retry cycle without human intervention.
This layered safety architecture ensures both hardware protection and operational precision.

Automation, Scheduling, and Resource Optimization

The automation logic is extended with an adaptive irrigation scheduling mechanism that responds to environmental conditions:
Decision-Based Scheduling:
On each scheduled day (Monday or Thursday at 5:00 AM), the system checks sensor data.
If conditions are not suitable, it postpones irrigation to the next day at 5:00 AM, continuously repeating the cycle until conditions are met.
Closed-Loop Operation: Once irrigation begins, the system proceeds through:

1. Sensor Check →
2. Wireless Link Establishment →
3. Thermal Image Analysis →
4. Precise Navigation & Irrigation →
5. Re-Analysis & Repositioning →
6. Return to Base (SSCU) →

By integrating smart condition-based scheduling, real-time feedback, and precise actuation, the system achieves maximal efficiency with minimal human oversight, delivering sustainable irrigation with significantly reduced power and water waste.
Each stage is internally validated to ensure accuracy, safety, and minimal resource use. Table 1 illustrates this performance which is measured through the efficiency outcomes.

Table 1 : Overall Efficiency Metrics

Parameter	Efficiency Outcome
Energy Usage	Up to 70% savings via smart scheduling and control
Water Utilization	50–65% reduction through targeted irrigation
Communication Uptime	98% success rate in field communication tests
Fault Recovery	Corrective response in under 1.5 seconds
Missed Irrigation	Automatically rescheduled for next valid time window

IX- conclusion

The proposed system demonstrates a practical and scalable solution for smart landscape irrigation using a fusion of environmental sensing, image processing, and IoT-based automation. By distributing the irrigation process on two units (a centralized sensing and supply unit (SSCU) and a responsive mobile sprinkler unit (ISV)), the system enhances control over where and when water is applied, significantly reducing unnecessary consumption. The integration of wireless communication between microcontrollers and intelligent decision-making algorithms ensures precise and adaptive irrigation under varying environmental conditions. Future enhancements may include ML-based irrigation scheduling, solar-powered components for energy autonomy, and real-time data analytics for further optimization. Overall, the system offers a promising step toward sustainable, high-efficiency water management in both agricultural and urban green settings

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