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Development of an Automated Line-Following Robot for Intelligent Plant Irrigation

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***Abstract*—Precision irrigation is very much crucial for the betterment of water usage and improvement in agricultural productivity. This paper presents the design of an autonomous line-following robot for efficient plant irrigation, integrated with infrared sensors for navigation, ultrasonic sensors for obstacle detection, plant recognition, and soil moisture sensors for controlled watering. The proposed system contributes to the literature by overcoming some limitations in the literature regarding previous automated irrigation methods in terms of adaptability and efficient use of resources. It provides a clear methodology regarding the integration of hardware-software components, system workflow, and decision-making process. The performance of the system is evaluated based on experimental analysis regarding preciseness of irrigation with less water wastage. Comparison analysis on methods will help in highlighting the advantages of the proposed approach for better accuracy and efficiency. The results confirm the reliability of the system, and confirmatory key metrics provide its practical applicability in smart agriculture.**

Keywords—Automation, Line-following robot, Soil moisture detection, Ultrasonic sensor, Plant irrigation.

I. INTRODUCTION

Water resource management and agricultural automation represent two important keys to proposed solutions for growing food insecurity, shortages of water, and consuming resources responsibly. The FAO reports that 70% of the world's freshwater withdrawals go toward agriculture, underscoring the urgent need for creative approaches to water efficiency [1]. A more sustainable, technologically higher-order agricultural system is called for by the concept of food security for the generations to come in view of fresh water demand emergence due to effects of climate change, urbanization, and increase in population.

Tackling problems, including resource conservation and manpower constraints in agriculture, depends on efficient water management and automation [2]. Effective solutions have developed from automated systems, therefore enhancing sustainability and output. This work presents a new line-following robot with automatic watering capabilities based on ultrasonic sensors and soil moisture detecting capabilities. Designed to follow a predefined path, the robot avoids obstructions and detects vegetation close by. Consistent monitoring of soil moisture levels drives the irrigation system to turn on when the detected moisture levels fall below a designated threshold [3]. Using RFID-based plant detection at first proved challenging in terms of operational scalability and detection accuracy. We improved those points with ultrasonic sensors because of their excellent plant identification and flexibility. The modular design of the robot guarantees adaptability in most environments, agricultural areas, and metropolitan gardens. Future developments will be mainly devoted to improving the identification of the plants and precision in watering through advanced techniques such as computer vision and machine learning.

II. RELATED WORK

IoT solutions ThingSpeak and Blynk alert and track real time. Testing reveals the approach cycles soil moisture from 30–35% to 68.2% to retain ideal conditions. Modularity and IoT connectivity help to improve scalability, usability, and control by means of which the system is fit for both home gardening and agriculture [4]. However, the system has limits. Its internet connectivity requirement limits IoT capabilities like real-time monitoring and notifications in locations with poor networks. The current implementation only considers soil moisture, ignoring temperature and humidity, which are essential for irrigation control.

By combining sensors and microcontrollers, the studied systems effectively automate plant irrigation, therefore drastically lowering water waste and manual intervention [5]. Their restrictions, however, include reliance on consistent power or internet connectivity and a lack of adaptation to several environmental conditions including temperature and humidity. An inexpensive smart micro robot that uses RFID identification, soil moisture monitoring, and wireless connection to water indoor plants autonomously is presented in the paper [6]. The system's lack of obstacle avoidance and predefined navigation path limit its adaptability to complex or dynamic situations.

This study proposes a robust and precise line-following robot that uses PID controllers and multi-sensor integration for effective navigation and obstacle detection, making it ideal for industrial and controlled interior situations [7]. The technology is limited to navigation and obstacle avoidance and requires specified courses, making it unsuitable for smart agriculture and other applications. For automatic plant watering, Arduino UNO, GSM modules, and sensor circuits monitor soil moisture, temperature, and water levels. The system's smartphone app for notifications and remote control simplifies family gardening and agriculture [8]. It integrates IoT well, but the responses through GSM and warnings inhibit automation. Predefined sensor sets may require frequent human intervention due to limited environmental adaptation in dynamic agricultural scenarios.

It does a good integration of IoT, but the responses through GSM and warnings inhibit automation. Due to the limited environmental adaptation, predefined sets of sensors may require frequent human intervention in dynamic agricultural scenarios. Evaluation of Robotic Systems

IoT-based automated irrigation systems monitor the soil moisture, therefore optimizing the resources in a cost-effective and scalable way for any size of agricultural business. They are infrastructural, with real-time monitoring, though non-mobile, unlike robotic systems, and they cannot navigate a field dynamically. The navigation of robotic systems can be done on a lot of terrains while doing multi-parameter jobs, but they are more expensive and complicated to build. While IoT technologies are better for fixed applications, robotic systems excel in large, unstructured spaces [10].

SL	Paper	Technology Used	Features	Limitations
1	Design a Smart Mini Robot for Indoor Plant Watering System (Aqeel Rahman, 2022)	Arduino Mega and UNO, RFID technology, Zigbee-based Xbee modules.	RFID tags are used to identify plants.	Costly because a dedicated microcontroller for each plant tub is needed.
2	Automatic Plant Watering System using IoT (Swapnil Bhardwaj, 2018)	Arduino Uno, soil moisture sensor, IoT.	Prevents over-watering.	The model is not movable which is not efficient.
3	Design and Implementation of Line Follower Robot for Automatic Watering of Orchid Plants (Aep Setiawan, 2024)	ESP32 microcontroller, infrared sensors.	Adjustable speed, emergency stop functionality.	Did not have any mechanism for detecting soil moisture levels.
4	Automatic Watering System for Plants with IoT Monitoring and Notification (Jacquline M.S. Waworundeng, 2018)	IoT-based sensors, cloud computing.	Consider weather condition while watering.	High initial costs to build the model, the need for water pipes for all plant tubs

TABLE I. COMPARISON OF DIFFERENT AUTOMATIC PLANT WATERING SYSTEM MODELS

III. METHODOLOGY

The proposed model is designed for plant watering and navigating path automatically with the combination of microcontroller, sensors, and actuators. In this section we demonstrate the system's architecture, working mechanism and algorithm in details for efficient operation.

A. Components Used

The robot is built with the following key components:

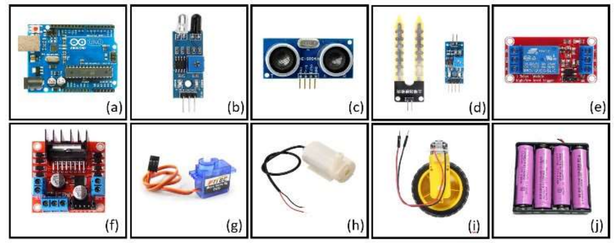

Fig. 1. Shows the (a) Arduino UNO, (b) IR Sensor, (c) Ultrasonic Sensor, (d) Soil Moisture Sensor, (e) Relay Module, (f) Motor Driver, (g) Servo Motor, (h) Water Pump, (i) Gear Motor, (j) Power Supply

The following Table II. shows detail list of models and specification of components used in the Automatic Plant Watering System including microcontroller, sensors, actuators, power supply.

TABLE II. MODEL AND SPECIFICATIOS OF COMPONENTS

Label	Name	Model	Specifications
(a)	Arduino	UNO R3	14 digital I/O pins, 6 analog inputs, USB port
(b)	IR Sensor	LM393	Operating voltage: 3.3–5V
(c)	Ultrasonic Sensor	HC-SR04	Range: 2cm–400cm, Operating voltage: 5V
(d)	Soil Moisture Sensor	LM393	Analog and digital output, Operating voltage: 3.3–5V
(e)	Relay Module	SRD-12VDC-SL-C	Voltage: 6-12V, Max current: 10A
(f)	Motor Driver	L298N	Voltage: 5–35V, Max current: 2A per channel
(g)	Servo Motor	FS90	Operating voltage: 4.8–6V, Torque: ~1.5 kg-cm
(h)	Water Pump	Mini Submersible Pump	Operating voltage: 3–6V, Flow rate: ~80–120 L/h
(i)	Gear Motor	TT Motor with Wheel	Operating voltage: 3–12V
(j)	Battery Pack	18650 Li-ion Battery Pack	Voltage: ~7.4V (per pair in series), Capacity: varies

B. Working Mechanism

The robot operates in the following sequence:

1. **Path Navigation:** IR sensors detect black lines on a white surface, signaling the robot to follow the lines. The Arduino Uno processes IR sensor data and controls the gear motor to follow the path.

2. **Obstacle Avoidance:** Ultrasonic sensor is used to detect whether there is any obstacle in front of the robot.

3. **Plant Detection:** Ultrasonic sensor is also used here to detect plant tubs.

4. **Moisture Detection:** When the robot detects a plant, stops there and servo motor with soil moisture sensor moves toward the tubs soil and the moisture sensor checks the soil's moisture level.

5. **Water Dispensing:** If the moisture is below a predefined level, the relay module activates the water pump until the soil moisture level rises.

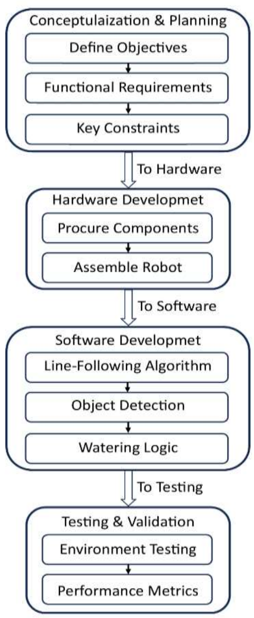

Fig. 2. Project Development Workflow

Fig. 2 shows a systematic workflow of how the autonomous irrigation system goes through four stages of development: Conceptualization & Planning, Hardware Development, Software Development, and Testing & Validation. Such a sequence will provide seamless integration of objectives, assembly of components, functional logic, and performance evaluation for efficient irrigation.

C. *Algorithm*

The working functionality of the robot is based on the following algorithm:

1. Activate all the components and sensors.
2. Follow the black line using IR sensor data.
3. Check continuously to detect obstacles with ultrasonic sensors. If an obstacle is detected, overtake and realign to the line.
4. If a plant tub is detected - Measure the soil moisture levels. If the soil is dry, activate the water pump until the soil get enough moisture.
5. Again, start to follow the line after watering.
6. Repeat steps 2 - 5 until all plants are watered.

The methodology integrates precise sensor inputs, efficient line-following, movable arm with soil moisture sensor and watering using water pump. This method ensures a reliable system to automate the irrigation process with reduction of human involvements and improvement of operational efficiency.

Fig. 3 shows how the proposed system works. It will be observed that the robot will follow the line of black, avoid obstacles, and detect plants. This will further check the soil moisture to turn on the water pump if necessary. The process keeps going until the robot is finally out of the path and shows real-time autonomous irrigation.

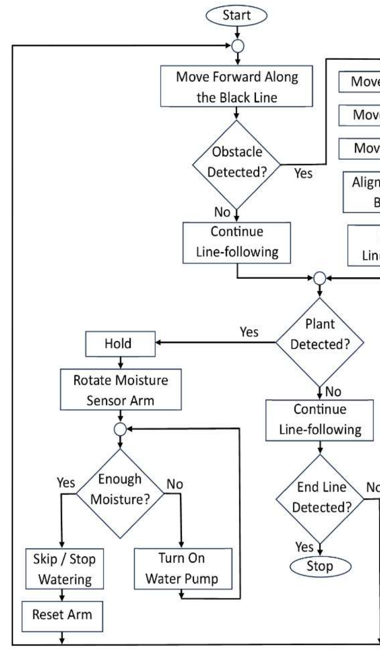

Fig. 3. Flowchart of the system's operation

IV. Implementation

The circuit integrates all components as shown in the Fig. 4. Digital pins allow the IR sensors to detect paths. For readings on soil moisture, the moisture sensor connects via analogue pins. Obstacle detection uses ultrasonic sensors coupled to trigger and echo pins. Two DC motors are run under supervision of the L298N motor driver. Under battery pack power, the relay module runs the water pump.

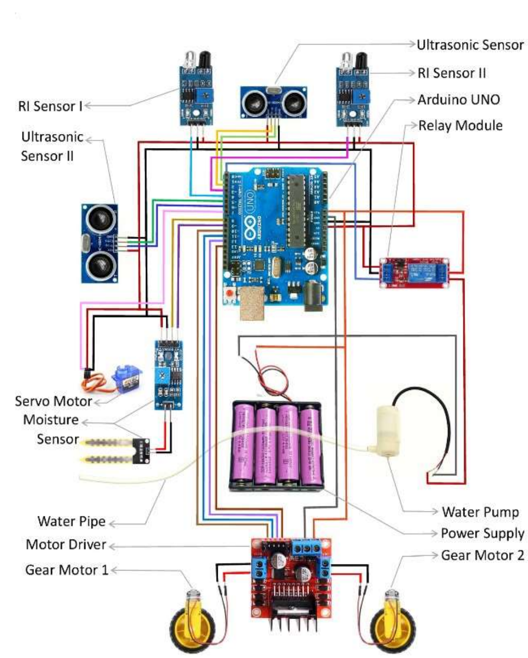

Fig. 4. Circuit Diagram of The System

A. Hardware Implementation

Assembling the robot chassis, mounting sensors, and matching components based on the circuit design forms the hardware implementation. Important actions consist:

1. Setting the IR sensors at the front of the robot.
2. To increase accuracy of watering attaching the water nozzle next to the soil moisture sensor.

B. Software Implementation

The code is written using Arduino IDE to integrate sensor readings and control gear motors, servo motor and water pump.

V. Results and Discussion

Line follow was able to trace the line followed correctly, determining the path based on IR sensors detecting a black line against a white background. An ultrasonic sensor detected the obstacle and container of plants efficiently. A soil moisture sensor checked for the wetness of the soil in case there was any urgent need for water. During the test, it was able to identify a plant container and estimate the soil moisture level in less than five seconds. Watering also worked great, with no incidents of overwatering, hence very responsive to the condition of the soil. The ultrasonic sensor employed in the detection of plants was used as an alternative due to the limitation presented by the Arduino Uno on digital input output pins.

Although it generally worked fine, the robot had problems following faded line paths. The results realized did not majorly affect the performance of the robot in terms of navigation, obstacle detection, and watering with precision. Quantitative tests were able to measure that the whole system could find and irrigate the plants within less than 10 seconds. In this respect, it provides efficiency in irrigation. The functionality of the soil moisture detection function of the robot maintains the soil moisture threshold below 30-60%, guaranteeing adequate water supply to plants without over-irrigation. Table III shows the overall performance of our model based on the metrices including line following accuracy, soil moisture detection, irrigation time, moisture threshold maintenance.

TABLE III. Performance Metrices of The Model

Metric	Measured Performance	Remarks
Line Following Accuracy	Struggled with faded lines	Improvement requires.
Soil Moisture Detection	Measured within < 5 seconds	Fast response.
Irrigation Time	Watering completed within < 10 seconds	No overwatering observed.
Moisture Threshold	Maintained soil moisture between 30-60%	Ensured efficient water usage.

The hardware and software resources of our work can be found at: https://github.com/Noor210111/Development-of-an-Automated-Line-Following-Robot-for-Intelligent-Plant-Irrigation

VI. Conclusion

This application uses a line-following robot to efficiently automate the watering procedure by means of which one can Thanks to the mix of sensors and actuators, which guarantees a precise and economical operation, it is appropriate for uses in the field of smart agriculture.

In future the combination of computer vision and machine learning algorithms possesses significant improvement of accuracy and efficiency of the robot. This research addresses the urgent necessity for resource optimization and environmental protection, contributing to the creation of scalable and sustainable solutions for contemporary agriculture.

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