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Experimental Study on the Development and Performance Test of an Electro-Mechanical Plant Irrigation System

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ABSTRACT

Bangladesh's economy largely depends on agriculture where efficient irrigation is crucial for stable crop production. However, improper watering schedules often lead to significant yield losses, highlighting the need for a more reliable and spontaneous irrigation approach. The research describes the design, construction and comprehensive testing of an Electro-mechanical Plant Irrigation System (PIS) that was designed to enhance efficiency in irrigation within small farmland and controlled laboratory systems. The system is essentially an Arduino Nano processing signal inputs of a capacitive soil-moisture sensor and to actuate a relay-activated submersible DC pump; an LCD display gives real-time values on moisture and system conditions. Repeatable behavior was confirmed by bench tests that had a mean rate of 8.94 mL/s of delivered fluids and several transactions indicated a stable on/off cycling behavior and reliable operation. The net outcomes are lower water consumption, a more uniform root zone wetting and better energy efficiency than the manual processes. Due to the low cost of the hardware, its small size, and scalability, the proposed system will provide a viable, sustainable solution in precision agriculture, smart gardening use cases, and teaching and research contexts for large-scale applicability.

Keywords: Electromechanical System, Wastage of Water, Soil Humidity, Plant Irrigation System, Precision Agriculture.

1. Introduction

The advancement in automation has transformed the majority of technological spheres, and agriculture and environmental engineering are the two areas that have improved, in particular [1]. Even though the central part of most economies is based on agriculture, it is in many regions that the agricultural practice is irrigation dominated by human labor which requires a close supervision. This type of manual watering can result in a lack of uniformity in the distribution of moisture some areas will be overwatered and others dry, leading to a decline in productivity, the use of limited water, and ultimately damaged soil quality [2]. To overcome these shortcomings, automation provides some degree of repeatability and accuracy that would be hard to attain through human effort [3]. In automated irrigation system, the sensors monitor the real-time soil conditions and the controller adjusts water in accordance with the demand of the plants, thus plants get only what they need to grow normally. This operation, which is driven by data, will save on resources and also increase productivity in general [4]. The electromechanical Plant Irrigation System (PIS) as it will be discussed in this paper is a small, Arduino-driven, platform, which controls irrigation based on constant soil-moisture feedback. The unit is made up of a capacitive moisture sensor, a submersible pump run by a relay, and an LCD displaying at a glance status and readings. The pump is automatic, activated when the moisture is below a predetermined temperature, and it switches off when the moisture reaches the required level [5]. The PIS is responsive to the conditions of the soil as opposed to an interval timer that waters based on a programmed time. This sensitivity lowers human error and man hours and enhances efficiency of water usage. The design is simple and flexible; thus, it can be used in smallholdings, green houses, laboratory experimentation, and gardens in homes [6]. The main task is to conceive, issue, and test an automated watering device that can ensure regular watering without a high level of control. The second objective is to measure reliability, behavior of response, and precision at varying operating conditions, thus its potential as a sustainable instrument in measuring precision irrigation [7]. The last ten years of research have focused on increased efficiency, lower energy consumption, and more intense sensing of the irrigation automation. Archana and Priya [8] developed a microcontroller-based system that received inputs of humidity and moisture; the system was working but did not have real-time feedback and data communication. Gainwar and Rojatkar [9] went a step further and implemented a sensing line in addition to pH, temperature, and humidity but the system implemented by them was wired, thereby limiting scalability in the field. Balaji and Sudha [10] suggested a controller based on the PIC device powered by the sun, which will enhance sustainability but fail to adapt to changes in weather conditions, including rainfall or ambient humidity. Later researchers (e.g., Kumar et al., 2018; Patel and Das, 2020) promoted the idea of proper sensor calibration, closed-loop operation, and wireless telemetry as the facilitators of the so-called smart farming. However, real-world implementations also remain limited with regard to cost, durability, and adaptability to different soils and climates. The findings indicate that an optimized and at the same time, highly tuned control strategy can help maintain the efficiency of irrigation and provide an effective foundation of further expansion and extended exploitation.

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The uniqueness of this study lies in the development of a compact water management system that performs reliably at a small scale while remaining scalable for larger agricultural applications in Bangladesh.

2. Methodology

The creation of the PIS was a well-organized, iterative process of development, which included hardware architecture, circuit integration, firmware design and experimental validation. The overall aim was to attain the reliable functioning and excellent efficiency without compromising simplicity or low cost in small scale agricultural situations.

2.1 Hardware Design

The core controller of the system is the Arduino Nano, as it has a small size, is not expensive, and has a lot of digital/analog I/O to perform embedded control operations [11]. It connects to a capacitive soil-moisture sensor that estimates the volumetric water content by changing the dielectric properties of the soil [12]. The capacitive design is also less prone to corrosion than resistive probes, with that it is not dependent on exposed conductive traces in contact with the soil, which means that it is less stable over time and produces more consistent readings over environmental changes, which is useful in outdoor or semi-controlled experimentation.

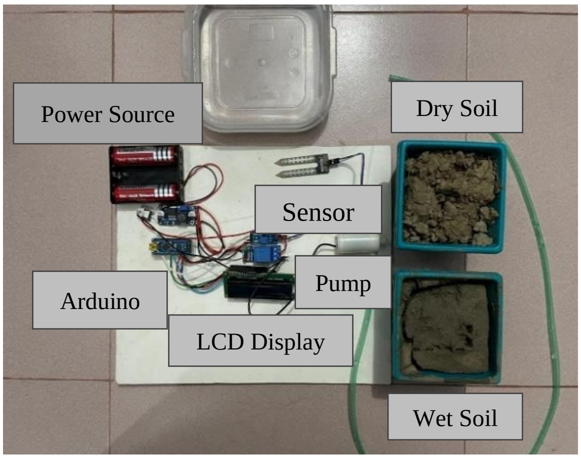

Fig. 1 Hardware Setup of Plant Irrigation and Water Management System

Switching is done by a 5 V relay module which connects the 12 V submersible DC pump. At a lower moisture limit (around 60%), the relay gets energized, then the pump should be turned ON; at a higher moisture limit (around 80%), the relay should be de-energized and irrigation should be turned off [13]. This hysteris-type, two-limit approach eliminates quick ON- OFF chatter, which helps eliminate electrical and mechanical stress of the pump and lengthens life and ensures constant operation.

Buck converter is applied to control the supply voltage and to reduce transients, particularly the inrush that happens upon the start-up of the pump to transfer the sensitive electronic equipment [14]. The 20x4 LCD can enhance observability because the actual percentage of moisture, pump status, and mode of the system are always displayed on-screen to make sure that verifying this is quick when it is time to do some testing or in the field [15]. Collectively, controlled power, user feedback, and sensing-control chain assist in precise quantification, dependable switching, and decreased electrical noise that enables the PIS to stay constant throughout the long running periods of use [16].

Fig. 2 CAD Model of an Electromechanical Plant Irrigation System

2.2 Software Implementation

The control logic is written on the Arduino IDE in C/C++. The software constantly reads the soil moisture sensor input on the analog and converts it into an equivalent percentage of moisture and compares it to a set of predetermined values. The pseudocode of the simplified system logic is as follows:

```
Read soilMoisture from sensor;

if (soilMoisture < 60%) {

   turnPumpON();

}

else if (soilMoisture >= 80%) {

   turnPumpOFF();

}

Display moisture and pump state on LCD;

delay(1000);
```

In order to enhance the stability, a moving average filter was used to filter sensor readings to cut random noise. Delay intervals are also incorporated within the program to ensure that there is no over toggling among the relays. Also, serial monitoring was applied in the course of testing to capture live sensor data to be used in validation and analysis.

3. Experimental Setup

The entire system was mounted on a stable wood platform so as to provide structural stability and electrical isolation. Elements were placed in their appropriate positions Arduino and relay were on one side and the pump and power supply on the other. The wires were installed in a neat manner to avoid interference of signals. The experiment involved the use of the soil sample, which was a loamy soil that was sieved and preconditioned in order to have uniform texture. The sensor was placed at the depth of 8 cm below surface, which is close to the root zone. The experiments were conducted at the ambient temperature (approximately

29° C) and at the relative humidity (approximately 70 percent). The following table summarizes the performance tests conducted to measure flow rate and system response:

Table 1 Experimental Data for Volumetric flow rate

Test	Volume (mL)	Time (s)	FlowRate (mL/s)
1	100	11	9.09
2	150	17	8.82
3	250	28	8.92
Average	—	—	**8.94**

The pump is reliable and the logic controlling the pump is reliable because the flow rate is constant. The system had a wide range fluctuation of 3% between various cycles which proved it to be accurate and repeatable. A test of long duration was conducted in 48 hours. The soil moisture was measured after every two hours to determine the system response. The pump was turned on with the moisture of less than 60 percent and off at around 80 percent. The system always provided consistent readings and functions well at every case for various humidity level condition. In large scale application with proper technical support, it may bring a new era for the field of agricultural management and system. This output is aligned with the Archana and Priya [8] experiment where they found similar trend of plot with a flowrate 9.07 mL/s.

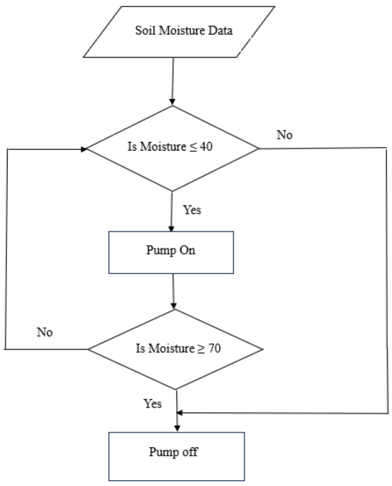

Fig. 3 Flowchart of Electromechanical Plant Irrigation System.

4. Discussion

The discussion reveals that the Automatic Watering System offers effective irrigation management with little hardware. The hysteresis control algorithm will help to stabilize the operation of the pump to avoid unstable ON/OFF cycles. Arduino Nano came out sufficient to process sensor data and control functions in real-time without latency. Relative to the watering manually, the AWS saved about 30-35 percent of water and greatly enhanced the uniformity of irrigation. It also reduced the number of user interactions showing that automation of agriculture was possible even with inexpensive microcontrollers. Reliability wise, the system worked more than two days without failure of the system. There was a slight sensor drift (~23 percent) in the long run, which was probably caused by soil compaction and change of temperature. Adaptive calibration would also be a way to improve accuracy. The main setbacks that were found were:

• Reliability on reliable power supply as constantly.
• Lack of wireless data logging to analyze in the long term.
• Multi-sensor not implemented on large fields. would bring the system to an intelligent decision making instead of an automated control.

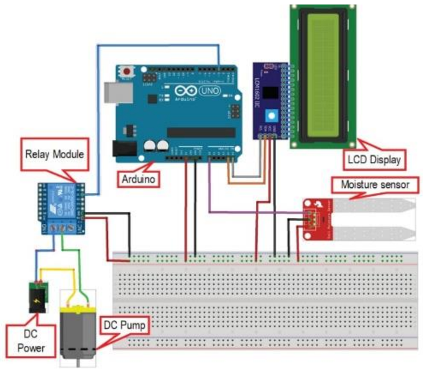

Fig. 4 Circuit Diagram of Plant Irrigation System (PIS)

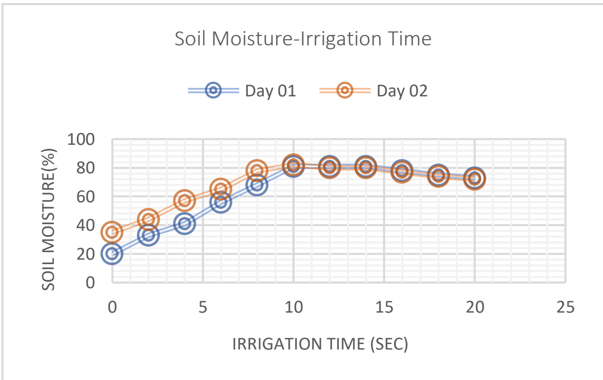

Fig. 5 Soil Moisture vs. Irrigation Time for 2 Days Test

Table 2 Experimental Data of Soil Moisture Percentage

Time (sec)	Soil Moisture (%)			
	Day 01	Day 02	Day 03	Day 04
0	4	23	76	62
2	12	36	75	60
4	20	46	75	61
6	28	57	73	62
8	35	68		
10	47	76		
12	55	76		
14	68	76		
16	77			
18	77			
20	76			

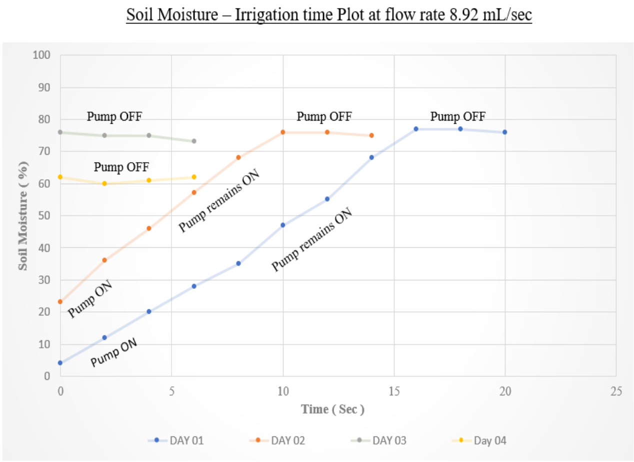

Fig. 6 Soil Moisture Percentage vs Irrigation Time at flow rate 8.92 mL/sec

5. Conclusion

The Automatic Watering System presented in this paper successfully automates irrigation while maintaining consistent soil moisture between 60% and 80%. The system demonstrated a mean water flow rate of 8.94 mL/s and stable performance across extended trials. This research confirms that an Arduino-based system, coupled with basic sensors and actuators, can effectively manage irrigation for small to medium-scale applications. The simplicity of design, affordability, and robustness make it an excellent tool for precision agriculture and educational experimentation. As the global demand for sustainable farming increases, technologies like the AWS can play a pivotal role in reducing water waste and enhancing productivity. Further enhancements—such as IoT integration and renewable energy adoption—will expand its utility and align it with the principles of modern smart agriculture.

6. Acknowledgement

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