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Design and Development of Smart Irrigation System in Paddy Field

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Abstract

This study evaluates the performance of a water pump and solenoid valve at specific water levels, as well as the consistency and reliability of a prototype smart irrigation system for paddy fields under laboratory-controlled conditions. The prototype was tested using a hysteresis-based control logic, where the pump is activated when the water level is less than or equal to 2.0 cm and the solenoid valve is activated when the water level is greater than or equal to 3.0 cm, until the target water level of 2.5 cm is achieved. A repeatability test consisting of 10 consecutive cycles was conducted to evaluate whether the water level could be maintained within the range of 2.0–3.0 cm. The results show that the pump operated effectively at water levels between 0.0 cm and 2.4 cm, while the solenoid valve functioned as intended at water levels of 2.6 cm and above. In addition, the repeatability test revealed that the pump exhibited a low overshoot ranging from 0.00 cm to 0.10 cm, whereas the valve showed a higher overshoot ranging from 0.15 cm to 0.30 cm. Experimental result show that the water level was consistently maintained within the desired range of 2.0–3.0 cm. These findings demonstrate that the proposed prototype operates reliably at the predefined water levels and successfully maintains stable water level control under laboratory conditions.

1. Introduction

As we know more than half of the world's population right now relies on rice as a staple food, and demand for it is rising each year, especially in Asian nations like Malaysia [1]. In order to achieve the best crop development and yield, the water management really important in paddy field farming. While over flooding may lower soil aeration and have a detrimental effect on root development, but insufficient water supply also might restrict photosynthesis and nutrient transport [2]. The traditional system in paddy field right now in Malaysia are still mostly irrigated using conventional techniques including manually controlled water canals and constant flooding [3]. Despite being straightforward, commonly and easy to used, these techniques always lead to high labour intensive, and bad control over water depth. In manual operation for control water, human mistake always happens, which could result in either excessive or insufficient watering, that impacting crop output and resource sustainability [4]. These drawbacks need to be taken seriously in finding or creating more accurate and automated watering systems.

In recent developments of smart agriculture where the system only irrigate when the soil moisture really low, the use of sensors like temperature, air humidity sensor and soil moisture sensor to monitoring the water in paddy field, microcontrollers-based Internet of Things (IoT) technology and pump or gate for automatic irrigation but it only for efficient water use at place that have low water resource like India [5][6]. At Malaysia we have lot of water resource so in this study we focus on developing the system that reduce the usage of labour energy and control water depth automatically using NodeMCU ESP8266 microprocessor, grove water level sensor, water pump and solenoid valve, the system uses automated control logic with hysteresis to control water input and drainage. So, whenever the water level under low threshold the pump will proceed fill water in paddy field while if the water exceeds high threshold, it will drain excessive water. Furthermore, an IoT-based monitoring platform is implemented to enable real-time observation of water level and actuator status.

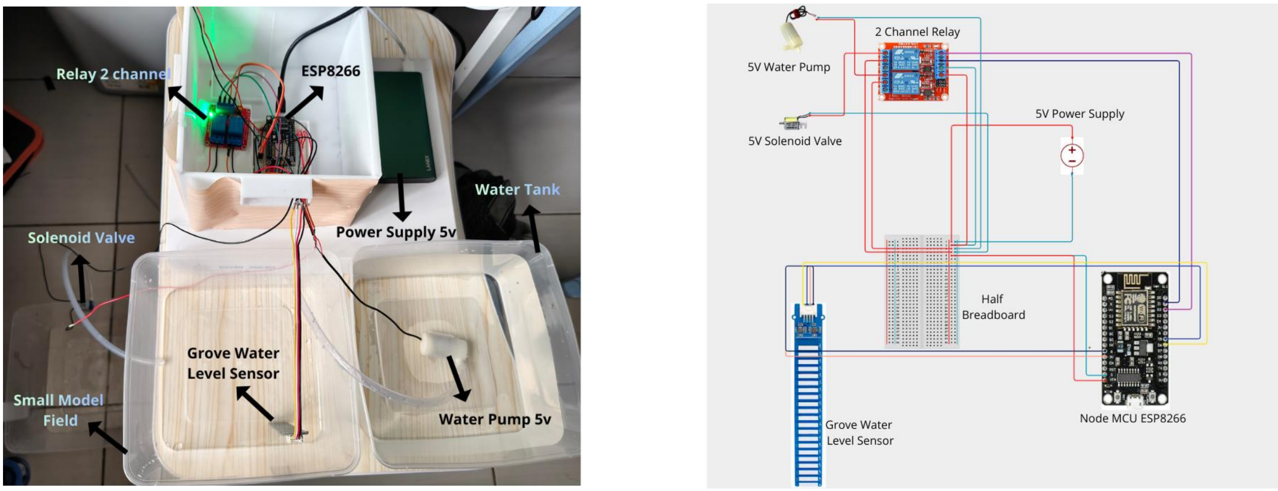
This study was conducted using a small-scale prototype under laboratory-controlled conditions. The primary objective was to evaluate the performance of two actuators, namely the water pump and the drainage valve, based on a predefined logic control strategy. In this system, the water pump is activated when the water level is less than or equal to 2.0 cm, while the drainage valve operates when the water level reaches or exceeds 3.0 cm. In addition, the system's consistency and reliability were assessed through a repeatability test consisting of 10 consecutive operating cycles. Each cycle began with water inflow into the paddy field model and ended with water drainage until the set target level of 2.5 cm was achieved, while ensuring the water level remained within the acceptable range of 2.0–3.0 cm. By bridging the gap between traditional manual irrigation practices and automated smart systems, this study demonstrates the potential to improve irrigation management efficiency while reducing the effort required to control water depth in paddy fields.

2. Methodology

The methodology of this study starts with the system design and hardware configuration, control logic, and software development, followed by performance testing. Lastly, following with data logging and analysis

2.1 System Design and Hardware Configuration

This section presents the system design and hardware configuration of the suggested smart irrigation system. The prototype design setup and schematic diagram of the smart irrigation system are shown in Fig. 1, which also demonstrates how the water level sensor, microcontroller, relay module, water pump, and solenoid valve used for automated water level control in the paddy field model are integrated.



(a) (b)

Fig. 1 Prototype Design setup (a); and Schematic Diagram(b)

The physical prototype design setup of the suggested smart irrigation system applied to a laboratory-scale paddy field model is depicted in Fig. 1(a). To continuously check the water depth, the Grove water level sensor is positioned vertically inside the model. Water is supplied to the model during irrigation by a water pump that is connected to an external water reservoir, and water discharge is managed by a solenoid valve at the drainage exit. To handle sensor data processing and actuator control, the NodeMCU ESP8266 microcontroller and relay module are positioned inside a box that can protect from contact with water when taking the result. This configuration enables safety and controlled laboratory testing of automatic water intake and outflow.

The schematic diagram of the smart irrigation system is shown in Fig. 1(b). The I2C communication protocol is used to interface the Grove water level sensor with the NodeMCU ESP8266 microcontroller. A two-channel relay module receives control signals for water pump and valve from the microcontroller after it has processed the sensor readings. The irrigation water pump is controlled by one relay channel 1, while the drainage solenoid valve is controlled by channel 2. The relay module will provide electrical isolation between the microcontroller and high-power devices properly. A 5V power supply will power the system, allowing the sensor and actuation components to operate smoothly.

2.2 Control Logic and Software Development

In this project the Arduino Integrated Development Environment (IDE) was used to implement the control logic of the suggested smart irrigation system into NodeMCU ESP8266 microcontroller. In order to maintain the required water level in the paddy field model, the software is in charge of analysing water level measurements, figuring out the system's working condition, and automatically controlling the water pump and solenoid valve.

In order to avoid frequent actuator switching, the control technique that based on a threshold-based hysteresis approach have been used. The pump starts level, the target water level, and the valve start level are the three water level reference values that are specified. These thresholds create a control band that minimizes oscillations brought on by minute variations in sensor readings and gives stable water level adjustment. IDLE, FILLING, and DRAINING are the three different modes in which the system functions. The logic operations for this system as shown in Fig. 2.

```
/* ===== HYSTERESIS LEVELS (cm) ===== */
#define PUMP_START_CM    2.0
#define TARGET_CM        2.5
#define VALVE_START_CM   3.0

/* ===== CONTROL MODE ===== */
enum Mode { IDLE, FILLING, DRAINING };
Mode mode = IDLE;
  /* ===== MODE TRANSITIONS (HYSTERESIS) ===== */
  if (mode != DRAINING && cm <= PUMP_START_CM) {
    mode = FILLING;
  }

  if (mode != FILLING && cm >= VALVE_START_CM) {
    mode = DRAINING;
  }

  if (mode == FILLING && cm >= TARGET_CM) {
    mode = IDLE;
  }

  if (mode == DRAINING && cm <= TARGET_CM) {
    mode = IDLE;
  }
```

```
/* ===== APPLY OUTPUTS ===== */
if (mode == FILLING) {
  digitalWrite(RELAY_PUMP, PUMP_ON);
  digitalWrite(RELAY_SOLENOID, VALVE_OFF);
  Serial.println("MODE: FILLING | Pump ON");
  pumpState = 1;
}
else if (mode == DRAINING) {
  digitalWrite(RELAY_PUMP, PUMP_OFF);
  digitalWrite(RELAY_SOLENOID, VALVE_ON);
  Serial.println("MODE: DRAINING | Valve ON");
  valveState = 1;
}
else {
  digitalWrite(RELAY_PUMP, PUMP_OFF);
  digitalWrite(RELAY_SOLENOID, VALVE_OFF);
  Serial.println("MODE: IDLE");
}
```

Fig. 2 Threshold-based hysteresis control logic for automated irrigation

The system's threshold-based hysteresis control logic is illustrated in Fig. 2. The system switches to the FILLING mode, activating the water pump to raise the water level, when the monitored water level falls below the pump start threshold. The system switches to the DRAINING mode, which opens the solenoid valve to release extra water, when the water level rises above the valve start threshold. The system switches back to the IDLE mode, which turns off the solenoid valve and pump, when the water level reaches the predetermined target level. In addition to ensuring seamless operation, this hysteresis-based mode transition eliminates abrupt transitions between drainage and irrigation states.

The microcontroller uses relay outputs to regulate the pump and solenoid valve based on the active mode. In order to permit water input, the solenoid valve is kept closed when the pump is turned on in the FILLING mode. In the DRAINING mode, extra water is removed by turning off the pump and activating the solenoid valve. Both actuators are turned off when the system is in the IDLE mode. This output control system will ensure that water inflow and outflow are carried out correctly in line with control decisions. The primary feature of the proposed smart irrigation system is the automated and stable adjustment of water levels in the paddy field model, made possible by the established this control logic.

2.3 Performance Testing and Evaluation

A small-scale paddy field model was used with controlled laboratory conditions to assess the effectiveness of the suggested smart irrigation system method. The testing settings chosen to focus on the dependability, stability, and functionality of the automated water level management system under various water levels. The first testing parameter recorded is performance of water pump and solenoid valve at certain water level, we used the water level range from 0.0 cm to 3.0 cm or more to simulate typical shallow water conditions in paddy field irrigation. The performance of irrigation and drainage limits were assessed by predetermined lower and upper threshold values in the system's configuration. The primary input for assessing system response was water level readings from the Grove water level sensor. For the Second testing, we involve several performance-related metrics, including overshoot behaviour for the water pump, solenoid valve, and control action repeatability. To verify that the water pump and solenoid valve were triggered appropriately when the measured water level exceeded

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the predefined threshold values, actuator response testing was conducted. Overshoot testing was done to find standard deviations from the intended water level after the pump or valve was switched off. The test for repeatability was carried out by putting the system through 10 trial irrigation cycles in order to assess the consistency of water level regulation.

To ensure proper mode transitions according to the hysteresis-based control logic, the system's operating modes (IDLE, FILLING, and DRAINING) were also monitored. The condition of the pump and solenoid valve was assessed through IoT monitoring. For later study, all sensor readings and actuator states were recorded. The results and discussion in the next part are supported by these testing parameters, which offer an organized framework for assessing the effectiveness and dependability of the suggested smart irrigation system. This section presents and discusses the experimental results obtained from the laboratory-scale evaluation of the proposed smart irrigation system. The performance are assessed in terms of water level control accuracy, the actuator's response, overshoot behaviour, and repeatability of operation under automated control.

3. Result and Discussion

The result will be divided into two sections the 3.1 Water Level Control Verification and 3.2 Overshoot Analysis involve together with calculation.

3.1 Water Level Control Verification

The initial test that we carried out was to verify that the water pump and solenoid valve were functioning correctly at various water levels. The reactions and status of the water pump and solenoid valve were noted as the water level was gradually changed from 0.0 cm to 6.0 cm. This test was performed to make sure that when the observed water level exceeds the predetermined lower and upper threshold values, the system will respond appropriately according to the logic setting in the methodology.

Table 1 presents the observed system behaviour at different water levels, including pump activation, valve activation, and idle state.

Table 1 Water level control verification results

Water Level (cm)	Pump Status	Valve Status	System Mode
0.0 – 1.9	ON	OFF	FILLING
2.0 – 2.4	ON	OFF	FILLING
2.5	OFF	OFF	IDLE
2.6 – 2.9	OFF	ON	DRAINING
≥ 3.0	OFF	ON	DRAINING

The result that we found indicates the system effectively turns on the water pump when the water level drops below or equal to the 2.0 cm until I reach 2.5 cm set target level and the solenoid valve when the water level is equal to or rises above the 3.0 cm Both actuators stay idle as long as the water level stays within the specified range of set target water level. This result is evidence that the both actuator pump and valve perform correctly based on objective state before.

3.2 Repeatability Test

The repeatability test was conducted in order to determine consistency and reliability of pump and valve during 10 consecutive cycles in reaching 2.5 set target water level and maintaining the water level within 2.0 cm to 3.0 cm. The pump overshoot was calculated using:

$$\text{Overshoot} = |\text{ Final water level after action} - \text{Target level }| \quad (1)$$

Table 2 Pump and Valve Overshoot Test Results at 2.5 cm target level

Trial Number	1	2	3	4	5	6	7	8	9	10
Peak water level after pumping (cm)	2.40	2.60	2.40	2.50	2.55	2.55	2.50	2.40	2.50	2.50
Overshoot Pump (cm)	0.10	0.10	0.10	0.00	0.05	0.05	0.00	0.10	0.00	0.00

Peak water level after draining (cm)	2.80	2.70	2.70	2.80	2.70	2.70	2.70	2.65	2.70	2.65
Overshoot Valve (cm)	0.30	0.20	0.20	0.30	0.20	0.20	0.20	0.15	0.20	0.15

Based on the experimental results, three test cycles did not reach the target water level of 2.50 cm. This occurred due to water surface ripples, which caused the water level sensor to detect the target level prematurely, resulting in the pump being deactivated at approximately 2.40 cm. In contrast, another three test cycles slightly exceeded the target water level. This overshoot occurred because, during pumping, the sensor detected the target level with a slight delay when the water level was close to 2.50 cm, allowing additional water to enter the system. For the remaining four test cycles, the water level reached the target value of 2.50 cm accurately, indicating precise sensor detection and timely pump deactivation at the set threshold.

In addition, no test cycle showed a final water level below the target value for the solenoid valve operation; instead, all 10 cycles exhibited a slight positive overshoot. This behaviour occurred due to the slow drainage flow rate in combination with the operating principle of the Grove water level sensor. The sensor detects water level based on discrete contact points along its sensing traces. When the water level drops below 3.0 cm, water continues to flow out; however, the sensor may still detect wet traces caused by previous water contact at higher levels. During slow drainage, sufficient time is available for these contact points to gradually dry, allowing the sensor to detect the 2.5 cm contact point and trigger valve closure prematurely. As a result, drainage stops before the water level fully stabilizes at the target value, leading to higher overshoot values for the solenoid valve in this prototype.

Overall, the repeatability test demonstrates that the prototype smart irrigation system is capable of maintaining consistent and reliable water level control over 10 consecutive operating cycles. The system successfully controls the water level within the range of 2.0–3.0 cm in all trials, confirming the effectiveness of the hysteresis-based control logic. The pump exhibited minimal overshoot, indicating precise control during the filling process, while the solenoid valve showed slightly higher overshoot due to slow drainage flow and the discrete sensing mechanism of the Grove water level sensor. Despite this limitation, the observed overshoot remained within an acceptable range and did not compromise overall system stability. These results confirm that it meets the objective of the study in maintaining the water level of 2.0 cm to 3.0 cm.

4. Conclusion

This study successfully designed and evaluated a smart irrigation system for paddy fields based on automated water level control under laboratory-scale conditions. The prototype smart irrigation system effectively controls water depth using a hysteresis-based control logic, maintaining the water level within the desired range of 2.0–3.0 cm. Experimental results confirmed that the water pump and solenoid valve operated according to predefined threshold levels, demonstrating accurate actuator response and stable mode transitions between filling, idle, and draining states. However, this study is limited only to small-scale protype under controlled laboratory condition. So, the factor such larger water volume, environmental disturbance, real big pump and valve were not considered. For future work, the system can be extended to real field scale implementation by using higher capacity pump and drainage mechanism, improving the sensor signal processing and incorporate adaptive water level control for different paddy growth stage. Furthermore, integration of cloud-based monitoring platform that more advance could further enhance real time data accessibility and decision making for real practical paddy field.

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Muhammad Sahimi Othman;* ***data collection:*** *Muhammad Sahimi Othman;* ***analysis and interpretation of results:*** *Muhammad Sahimi Othman, Afishah Alias;* ***draft manuscript preparation:*** *Muhammad Sahimi Othman, Afishah Alias. All authors reviewed the results and approved the final version of the manuscript.*

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