Journal of Engineering Research Innovation and Scientific Development 3 (2), (2025), 8-11 https://doi.org/10.61448/jerisd32252

Journal of Engineering Research Innovation and Scientific Development
journal homepage: www.jerisddelsu.com
Print ISSN 2971-6594 Online ISSN 2971-6608

Design and Construction of an Autonomous Pumping System

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Article history: Received: 23-03-25, Revised: 27-04-25, Accepted: 01-05-25, Published: 10-05-25

Abstract

This paper presents the design and development of an automated water level monitoring and pumping system that utilizes ultrasonic sensors for precise water level detection. The system integrates an Arduino Mega microcontroller with sensors and a relay module to control pump operation. It autonomously activates the pump when the water level falls below a predefined threshold and deactivates it upon reaching the desired high level, thereby minimizing human intervention and reducing water wastage. Experimental results demonstrate that the system responds rapidly, with a one-second activation and deactivation time for the pump after detecting changes in water level, ensuring efficient and reliable operation. This study addresses limitations in existing solutions by incorporating a more robust microcontroller and high-precision ultrasonic sensors, enhancing both accuracy and reliability. The system is designed with affordability in mind, making it suitable for deployment across various settings. Additionally, its modular architecture enables scalability and adaptability to different operational requirements. This research contributes to the field by demonstrating the feasibility of a cost-effective, microprocessor-based autonomous pumping system that employs readily available conductive materials for level detection. The proposed design provides a practical and efficient solution for sustainable water management in both domestic and industrial applications.

Keywords: Automation; Pump; Sensor; Actuator; Control system

1. Introduction

Water, a fundamental resource for life and economic development, plays a crucial role in sustaining both terrestrial and aquatic ecosystems. Effective water management is essential not only for human consumption and industrial processes but also for the preservation of aquatic habitats. The urgency for improved water management is underscored by global challenges such as climate change and population growth, which exacerbate water scarcity and demand. The World Economic Forum has identified the water crisis as the most significant global risk in terms of societal impact over the next decade (World Economic Forum, 2015). Additionally, the World Health Organization reported that over 750 million people globally lack access to safe drinking water (World Health Organization, 2014). This situation highlights the critical need for efficient water management systems that minimize waste and ensure sustainable usage. One effective approach to managing water resources involves the implementation of automated water level control systems. These systems can help in maintaining consistent water supply, particularly in industrial settings, agricultural irrigation, and domestic applications, thereby reducing human intervention and the associated risks of negligence and inefficiency.

Industries, agricultural enterprises, and residential areas require a constant and reliable water supply for various activities, including food processing, irrigation, and daily domestic use (Palanichamy and Kalpana, 2024). Monitoring water levels and manually operating pumps can be a repetitive and labor-intensive task, often leading to inefficiencies and potential water wastage. In industrial settings, such inefficiencies can translate into significant cost implications, particularly when dealing with distilled water or other costly resources. An automated system capable of accurately monitoring water levels and controlling pump operations can mitigate these issues by ensuring optimal water usage and minimizing human error(Praveen *et al.,* 2023).

This study proposes the development of an automated water level monitoring and pump control system utilizing an ultrasonic sensor for accurate water level detection, a relay module for pump control, and an Arduino Mega microcontroller for system integration and interaction with input sensors and output devices. The system is designed to automatically activate the pump when the water level falls below a predetermined threshold and deactivate it when the desired level is reached. This approach aims to provide a reliable and efficient solution for water management with minimal human intervention.

Several studies have explored various methods of automatic water level control and pump systems. Premi and Malakar (2019)developed an automatic water level and pump control system using ultrasonic sensors and an Arduino Uno. Their system aimed at preventing water overflow and dry running of pumps in domestic applications. Getu and Attia (2016) proposed a similar system for managing excessive water usage in residential and commercial settings, utilizing resistive sensors and integrated circuits for level detection and control. Al-Talib *et al.* (2024) addressed the high operational costs of traditional pumping systems by designing a solar-powered water pumping system, which significantly reduced energy costs and was particularly beneficial for underdeveloped areas. Joeng *et al*. (2023)andVijay *et al.* (2023) developed an Arduino-based control system for water reservoirs, integrating Blynk for remote monitoring and control, highlighting the importance of real-time data and remote accessibility. While these studies have made significant contributions, there remain gaps in terms of scalability, cost-effectiveness, and the integration of advanced microcontrollers for improved reliability and performance. Moreover, previous works have not sufficiently addressed the combination of various sensor technologies and their practical deployment in large-scale industrial applications.

This study addresses the existing research gaps by developing a comprehensive water level monitoring and pump control system that integrates ultrasonic sensors, relay modules, and the Arduino Mega microcontroller. By leveraging advanced ultrasonic sensors, the system enhances accuracy and reliability in water level detection while ensuring robust performance through the Arduino Mega. Additionally, it provides a cost-effective solution suitable for both small-scale domestic applications and large industrial environments. The proposed system is designed to be scalable and adaptable, allowing for easy customization to meet diverse operational requirements. Furthermore, by automating the water management process, the system minimizes human intervention, reducing errors and labour while promoting efficient water conservation. By addressing these aspects, the proposed system seeks to provide a practical and effective solution for modern water management challenges, ensuring sustainable and efficient use of this vital resource.

2. Methodology

2.1 Materials used

The materials utilized in this study include a relay module, a 5V DC water pump, an ESP32 development board, and a 2.7 kΩ, 1/4W resistor, all powered by a 5V, 2.5A power supply. The power requirements for the 5V DC water pump and the ESP32 development board are summarized in Table 1, while Table 2 provides the specifications of the tank and pump used in the pumping system.

Table 1: Power requirement for the 5V DC Water Pump and EP32 Development Board

Component	Voltage (V)	Current (A)	Power (W)
1. 5V DC Water Pump	5	0.22	1.1
2. EP32 Development Board	5	0.13	0.65
3. Total power consumption			1.75

Table 2: Specification for the Tank and Pump in the Pumping System

S/no	Description	Value
1	Diameter of the reservoir tank	36 cm
2	Height of the reservoir tank	38 cm
3	Diameter of the storage tank	36 cm
4	Height of the storage tank	38 cm

5	Height of the support stand	76 cm
6	Pump's Flow Rate	1.2-1.6 L/min
7	Pump's Maximum Suction Distance	0.8m
8	Pump's Outside Diameter of Water Outlet	7.5mm
9	Pump's Inside Diameter of Water Outlet	5.0 mm
10	Operating temperature	< 80°C

2.2 Hardware Components

2.2.1 Relay Module

A single-channel 5V relay module (see Figure 1) is an electromechanical device employed to control the on/off state of a pump using electrical signals(Yulianto, 2023). This module facilitates the switching of higher voltage/current loads by a low-voltage control circuit. While not physically bulky, the module integrates essential connection terminals for ease of use. The module typically features six pins, each with a designated function as detailed in Table 3.

Figure 1: Single Channel Relay module

Table 3: Single Channel Relay Module Pin Description

Pin Number	Pin Name	Description
1	Relay Trigger	Input to activate the relay
2	Ground	0V reference
3	VCC	Supply input for powering the relay
4	Normally Opened	Normally open terminal of the relay
5	Common	Common terminal of the relay
6	Normally Closed	Normally closed contact of the relay

2.2.2 5V DC Water Pump

This work describes the implementation of a miniature 5V DC water pump for fluid transfer within the system. The pump is designed for low-power operation, utilizing minimal voltage and current to propel fluid over short distances. It typically features two wires, positive and negative, for power supply and activation. The pump is interfaced with a relay module to enable control through electrical signals.The pump operates within an input voltage range of 3V to 5V, making it well-suited for the system's low-power requirements. Additionally, its current consumption is as low as 220mA, further contributing to efficient operation. The pump's design prioritizes a maximum suction distance of 800 cm and achieves a flow rate between 1.2 and 1.6 L/min. Submerged within the system's reservoir vessel, the pump is intended for short-distance fluid transfer with minimal elevation gain. Activation is achieved solely through instructions received from the ESP Wi-Fi module via the relay module's activation channel.

2.2.3 ESP32 Development Board

The ESP32 development board serves as the core control unit of the system. This microcontroller is responsible for receiving sensor signals, processing data based on a pre-uploaded program, and sending control outputs to the relay module shown in Figure 2. The program is uploaded via the USB Type-A (USB-A) port located on the board. The ESP32 receives signals from sensors positioned in the reservoir tank and the storage vessel. These sensors typically utilize voltage variations to indicate fluid presence and level, respectively. Based on the received data, the ESP32 controls the relay module, thereby activating or deactivating the pump. Furthermore, the ESP32 acts as a communication hub. It transmits system status information wirelessly to connected devices within its network. Additionally, the system can be remotely controlled through any device connected to the network via the same wireless medium, enabling start-stop functionality for the pump and overall system control. A significant advantage of the ESP32 development board is its communication flexibility. It can be configured to utilize either Bluetooth or Wi-Fi for communication with other devices.

2.2.4 2.7 kΩ 1/4w Resistor

This work incorporates a 2.7 kΩ, 1/4 W resistor identified by a color code of red-violet-red-gold. The gold band signifies a tolerance of ±5%. Resistors with this color coding scheme allow for straightforward value determination. In this case, the red band denotes a value of 2, the violet band signifies 7, and the third red band acts as a multiplier, indicating 100 ohms. Therefore, the nominal resistance is calculated as 27 x 100 Ω = 2700 Ω. The resistor is primarily employed to regulate current flow into the relay module. The power supply adapter for the development board was deemed sufficient based on its specifications, eliminating the need for further current regulation at that stage.

2.2.5 5V 2.5A Power Supply

The system is powered by a 5V DC power supply with a maximum current rating of 2.5A. The power supply incorporates various protection mechanisms to ensure system reliability. These include short-circuit protection to safeguard components from damage during voltage spikes, overload protection, and overvoltage protection. Notably, the overvoltage protection is designed for extended operational life, exceeding 50,000 hours under typical operating conditions. The power supply serves as the primary source of voltage for the entire system, enabling signal transmission between various components. The detailed circuit design comprising all the above listed components is shown in Figure 2

2.3 System Description

Figure 3 presents the flowchart illustrating the operational principle of the system, followed by a comprehensive description of its overall functionality.

Upon system startup, the ESP Wi-Fi module retrieves water level data using a series of insulated conductive wires positioned within the reservoir tank. The conductivity principle dictates that submerged wires transmit a voltage signal to the microprocessor upon contact with water. This signal triggers embedded software routines within the microprocessor, which interpret the specific activated wire to determine the corresponding water level (e.g., 25%, 50%, etc.). The microprocessor employs a pre-defined algorithm to control the pump based on the detected water level. When the water level falls below a designated threshold (e.g., empty tank), the pump activates to refill the storage tank. Conversely, when the water level reaches a pre-set maximum (e.g., full tank), the pump deactivates to prevent overflow.Additionally, the system transmits water

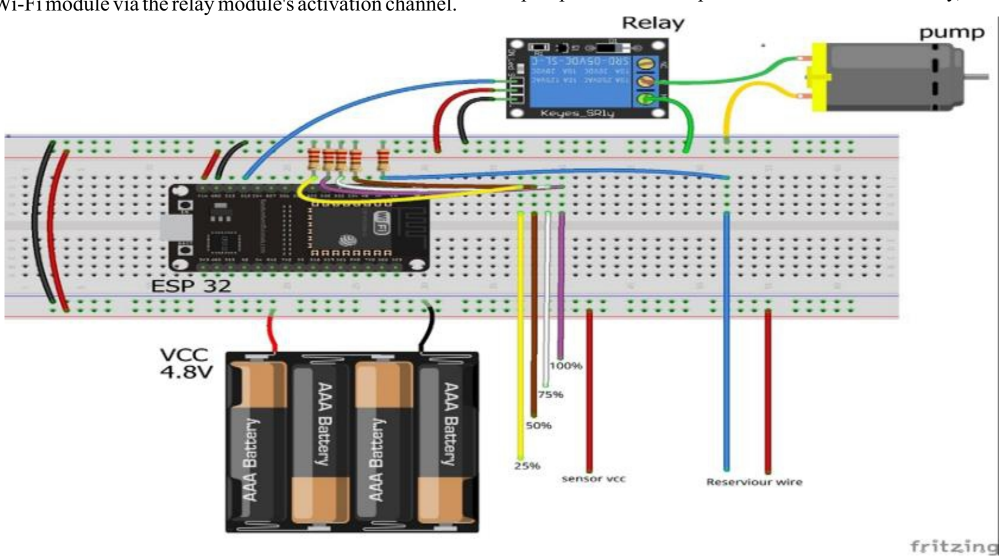

Figure 2: Circuit design

level information wirelessly to any connected device via the ESP Wi-Fi module. This enables real-time monitoring and visualization of water level data on a personal computer or any compatible device. The system incorporates safety features to protect the pump and prevent water wastage. The pump automatically deactivates when the reservoir tank is empty, preventing dry running and potential damage. This extends the pump's lifespan and ensures efficient operation.

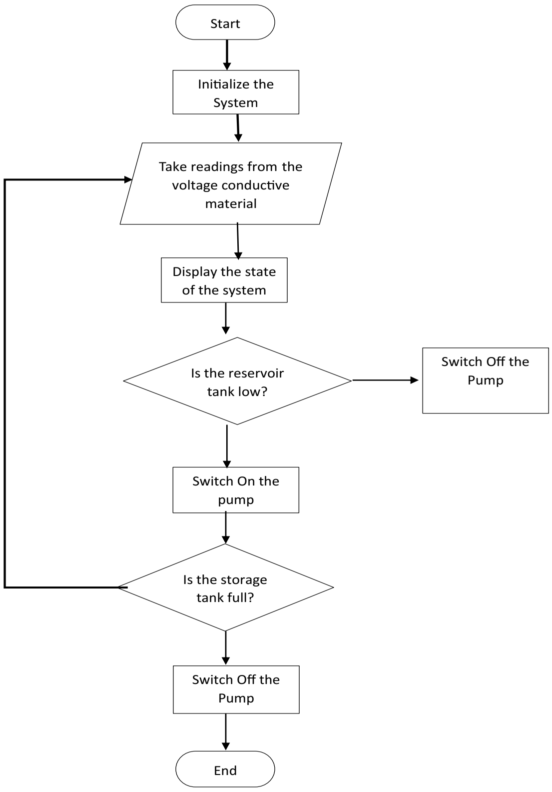

Figure 3: Flow chart of the system

2.4 Prototype Implementation

The autonomous pumping system prototype utilized two readily available plastic containers to represent the reservoir and storage tanks. Initial testing employed a breadboard to verify circuit functionality and identify potential connection errors. Following successful breadboard testing, the circuit components were transferred to a Veroboard for permanent connection through soldering. Electrical wires, chosen for appropriate conductivity and sensitivity, were connected to designated ports on the development board. This ensured proper signal transmission between various system components, including both input and output signals. Figures 4 and 5 shows the implemented and tested prototype.

3. Results and Discussion

3.1 System Response Speed

The response speed of the autonomous pumping system was evaluated based on the time taken for different operations. Table 4 summarizes the performance of the system, particularly its reaction to changes in water level conditions. The system continuously monitors the water level and updates its state every second. When the storage tank reaches its full capacity, the system takes approximately one second to deactivate the pump. Similarly, when the storage tank is no longer full, the system requires one second to reactivate the pump, ensuring efficient water level management with minimal delay.

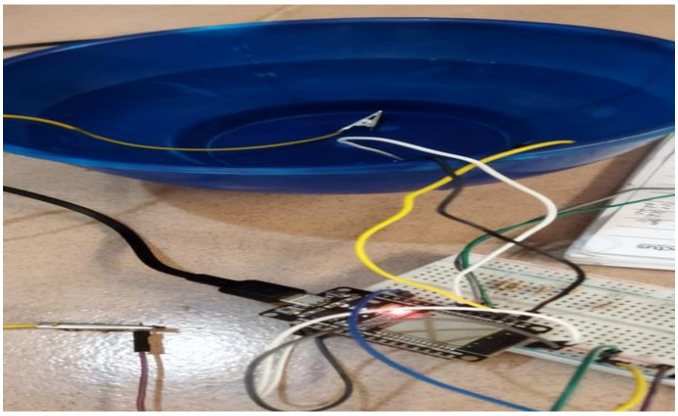

Figure 4: Connection to breadboard

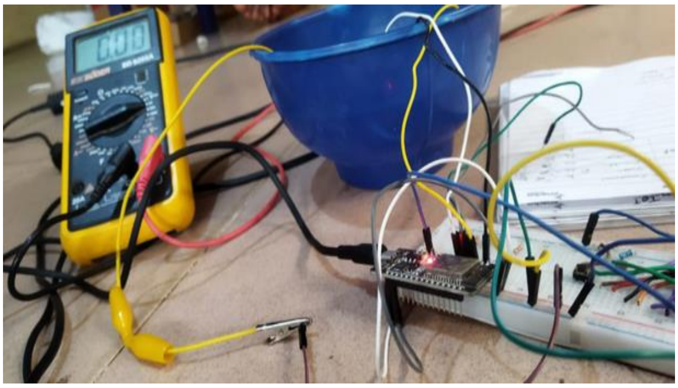

Figure 5: Tested Prototype

The rapid response time demonstrates the ability of the system to efficiently process water level signals and promptly activate the pump as required, a performance consistency also observed in the study by Olisa *et al.* (2021). This characteristic ensures continuous and reliable operation, reducing water wastage and improving system efficiency.

3.2 System Functionality and Performance

The autonomous pumping system operates based on a conductivity-based level sensing mechanism. Insulated conductive wires submerged in the reservoir tank serve as level sensors, transmitting voltage signals upon contact with water. These signals are processed by the ESP32 microcontroller, which runs an embedded control algorithm to determine the corresponding water level.

Upon detecting a low water level in the storage tank, the system promptly activates the pump, drawing water from the reservoir to refill the tank. Conversely, when the storage tank reaches full capacity, the system deactivates the pump to prevent overflow. The rapid response time of one second for both pump activation and deactivation ensures efficient and precise water level regulation. Additionally, the system provides real-time water level updates, allowing for remote monitoring and control through the ESP32's wireless communication capabilities.

One of the key advantages of this design is its safety and reliability. The insulated conductive wires used for level sensing pose no electrical hazard to operators, as they do not generate harmful shocks. Furthermore, the system incorporates preventive measures against pump dry-running, ensuring that the pump only operates when an adequate water supply is available in the reservoir tank. This feature extends the pump's lifespan and enhances overall system durability.

In comparison to traditional manual water level control, this autonomous system significantly reduces human intervention, thereby minimizing the risk of

Table 4: Response Speed of the System

S/N	Operation	Voltage signal	Response time
1	System state refresh rate	No refreshing is done as the system runs continuously	1 sec
2	Pump deactivation after full tank indication	1 sec	1 sec
3	Pump activation after low tank indication	1 sec	1 sec

negligence, water wastage, and operational inefficiencies(Agarkar *et al.,* 2023). Additionally, the use of low-power components, including the 5V DC water pump and ESP32 development board, ensures energy-efficient operation. The overall system design demonstrates high reliability, cost-effectiveness, and adaptability for various applications, including domestic water supply and industrial water management.

4. Conclusion

This study presented the design and development of an automated water level monitoring and pumping system, integrating an ultrasonic sensor for precise water level detection, a relay module for pump control, and an Arduino Mega microcontroller for system logic and interaction with sensors and actuators. The system autonomously activates the pump when the water level falls below a predefined threshold and deactivates it upon reaching the desired high level. This automation minimizes human intervention and reduces water wastage, thereby enhancing efficiency in water management.

The proposed system offers several advantages over existing solutions, including improved accuracy and reliability, cost-effectiveness, scalability, flexibility, and reduced human interaction. These enhancements address key limitations identified in prior research, particularly those concerning scalability, affordability, and the integration of advanced microcontrollers. Furthermore, this study extends the application of ultrasonic sensors to a larger-scale context compared to previous works that primarily focused on domestic implementations.

Future developments could explore the integration of a centralized monitoring system for managing multiple autonomous pumping units in industrial settings, facilitating real-time data collection and decentralized control. Additionally, incorporating on-site Human-Machine Interfaces (HMI) could improve user experience and system diagnostics. While this study employed water conductivity for level detection, alternative sensing technologies, such as ultrasonic or load-cell-based detection, could be investigated for their respective advantages and potential improvements in performance.

Overall, this work contributes to the field by demonstrating the feasibility of an affordable, microprocessor-based autonomous pumping system that utilizes readily available conductive materials for level detection. The proposed system provides a practical and efficient solution to modern water management challenges, promoting sustainability and responsible resource utilization.

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