ORIGINAL ARTICLE

Design of an Automatic Rooftop Water Tank Filling System and Measurement of Consumed Water for Home Appliance

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Abstract: This paper introduces a novel design and development of an automated water tank filling system. The system effectively regulates the operation of a water pump by monitoring the water level in a roof-top tank. Key considerations in the design include addressing power outages during pump operation, accommodating different tank dimensions, recording water consumption and implementing preventive measures against dry running of the pump. The installation and maintenance of the system are straightforward. The implemented system demonstrates successful control over the pump's operation, meeting the demands of household water usage. The experimental trial validates the practicality and effectiveness of the proposed design in efficient water resource management.

Keywords: Water tank automation; Float switch sensor; Magnetic contactor; Switch Mode Power Supply (SMPS); USBasp programmer.

Introduction

Water, being a precious natural resource, holds significant importance for all living beings since the inception of Earth. It plays a vital role in our daily activities such as cleaning, bathing, irrigation, and industrial processes. Despite covering approximately 71% of the Earth's surface, only a small fraction, less than 3%, is freshwater which is available for use. Moreover, the scarcity of freshwater is increasing, with approximately two-thirds of the global population experiencing water scarcity for at least one month each year [1]. Therefore, it becomes crucial to employ efficient water management practices, minimizing wastage and promoting sustainable usage.

In Bangladesh, the Water and Sewerage Authority (WASA) supplies water through pipes to major city corporation areas [2]. The water is typically stored in underground tanks in residential and commercial buildings. To access the stored water, city dwellers use water pumps to lift it from the underground tanks and transfer it to rooftop tanks for further use. The utilization of overhead tanks for water storage has also become popular in villages due to urbanization. However, the water management system presents several challenges that cannot be overlooked. One of the primary challenges is the manual operation of water pumps. Users are required to constantly monitor the water level in the tanks to switch the pump on or off, depending on whether the tanks are empty or full. This task can be burdensome and often leads to inconveniences in daily life. Residents may face unexpected water shortages during emergencies due to the sudden depletion of tank water. Conversely, forgetting to turn off the pump in a timely manner can result in water tank overflows, leading to wastage and unnecessary electricity consumption. At times, the water level in the ground reservoir or sump tank may decrease during the pump's operation, especially when there is low pressure in the WASA supply pipeline or during the dry season when the groundwater level drops. This situation can result in the pump drawing in air, posing a risk of damage. As a result, users are required to constantly monitor the water levels in both the ground reservoir and rooftop tank to ensure the pump operates correctly, which can be a tiresome task. Additionally, power outages may occur during the operation of the water pump due to insufficient power supply. If the user forgets to turn OFF the pump, it will remain active once the power is restored. Furthermore, city dwellers or tenants face the challenge of paying their water bills without knowing their actual water consumption.

In earlier studies, researchers primarily focused on developing efficient water management systems where the operation of water pumps was controlled based on sensor values. For instance, previous studies [3, 4] proposed automatic water pump controllers based on soil moisture sensing in agricultural fields or plant watering systems. In household water management systems, various sensors were commonly used to monitor water levels in storage tanks and enable automated pump operation. These included electrode-based sensors [5], water sensors [6], magnetic float sensors [7], and ultrasonic sensors [8]. Getu et al. [5] developed an electrode-based water level monitoring system integrated with an automatic water pump controller, utilizing the electrical conductivity property of water to determine the tank's water level. For water level monitoring, they divided the total height of the tank into nine segments, inserting a metallic electrode probe into each segment. The electrodes were connected to a voltage divider arrangement using series resistors (R1 and R2) and a supply voltage (V_{cc}). The floating terminals of the electrodes and the grounded bottom electrode formed the arrangement, as shown in Figure 1. Consequently, the output voltage became zero when an electrode was immersed in water due to conductivity property of water. A digital logic controller was used to control the water pump based on the highest and lowest voltage sensed by the electrodes. Another research work [9] utilized an electrode sensor to harvest water from municipal piped water. A single electrode was employed at the tank inlet to detect the presence and absence of water. To address the issue of floating analog values when the electrodes were not in a conducting medium, a pull-down resistor was implemented to ground the values. However, electrode-based systems could experience electrode corrosion over time, necessitating regular maintenance. Tanvir et al. [6] employed multiple water sensors for water level monitoring to automate the switching feature and water flow sensors for calculating water consumption bills of two different floors. This research encountered a limitation of fluctuating water consumption readings. Susheel et al. [10] designed an automatic water pump controller based on a float switch sensor, which included a floating bob that moved in response to changes in water level. When the water level was low, the bob rested at the bottom of the tank, while it floated at the top when the tank was full. The movement of the bob triggered a reed switch, responsible for opening or closing to activate the water pump through an electrical current. The limitation of this system was that it only turned on the pump when the tank had been completely empty. For contactless water level monitoring, ultrasonic sensors had been widely utilized. In comparison, the implementation of an ultrasonic sensor-based water level management system offered precise control and eliminated the issue of sensor corrosion due to its contactless nature. Additionally, a

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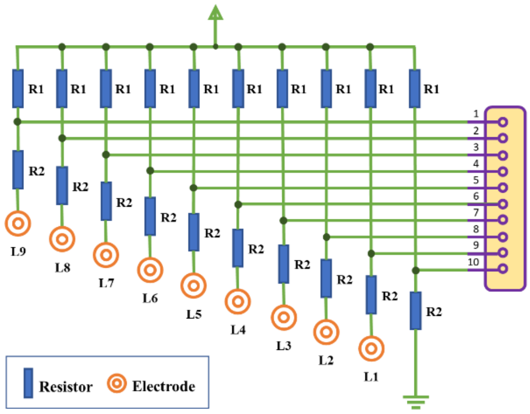

Figure 2. Electrode arrangement for water level determination of the reservoir.

research prototype [11] of an automatic water tank filling system successfully demonstrated the feasibility of accurately measuring the water level in the reservoir using an ultrasonic sensor, achieving an error value of approximately 3%. For water level detection, the ultrasonic sensor was installed at the top edge of the tank to emit a high-frequency sound and a microcontroller was used to measure the time of flight between the emitted and reflected signals. The distance between the water surface and the top edge of the tank was determined from the measured time. Then, the water pump was turned ON and OFF according to a pre-specified minimum and maximum water level, respectively, which was determined by the sensor. The water level was presented on a liquid crystal display (LCD) [12], in a LabVIEW front panel [13], or sent to a smartphone wirelessly [14]. In each system, the ultrasonic sensor module was bound to an Arduino microcontroller board to control the operation of the pump for automatic filling of the reservoir tank. Additionally, the authors [15] proposed an IoT-based microgrid smart water management system. They also utilized an Arduino controller board along with ultrasonic and GSM module for storing data on the cloud to analyze water consumption and monitor the real-time height of the water tank in each house of the community.

In this paper, we designed and developed an automatic water tank filling system with the aim of minimizing water wastage, reducing power consumption, protecting the water pump from damage, and improving overall comfort for individual households. Additionally, we incorporated a real-time water level monitoring system based on an ultrasonic sensor attaching at the rooftop tank and a mechanism to measure the amount of water consumption.

Materials and Methods

The proposed system utilized electronic components, including the ATmega328p microcontroller chip from the 8-bit AVR family, operating at 5V and equipped with 1 KB EEPROM. Figure 2 depicts the pin diagram of this microcontroller. To facilitate programming, an Arduino Nano board, which integrates the ATmega328pmicrocontroller, was employed, utilizing the Arduino Integrated Development Environment (IDE). The Nano board came preprogrammed with a bootloader, enabling code uploads without the need for an external hardware programmer [16]. Initially, the system algorithm was developed and implemented using the Arduino IDE on a small test platform. The algorithm was then burned onto the ATmega328p chip using AVRdude software [17] and a USBasp programmer. For compactness and cost-effectiveness, the programmed ATmega328p chip was used instead of the Arduino Nano board on the final printed circuit board (PCB). For non-contact water level measurement, an ultrasonic sensor module (HC-SR04) was employed, comprising a transmitter, receiver, and controlling circuitry. Other components included a 16x2 liquid crystal display (LCD) for displaying messages and indications to the user, a switch mode power supply (SMPS model: SRD-05VDC-SL-C) for efficient power conversion from 220V AC to 5V DC, and an electrically operated relay (model: SONGLE SRD-05VDC-SL-C) for switching a magnetic contactor (META-mec LS GMC-22 series) to operate the water pump are illustrated in Figure 3. Additional components such as Cat-4 cable facilitated sensor connectivity, push buttons

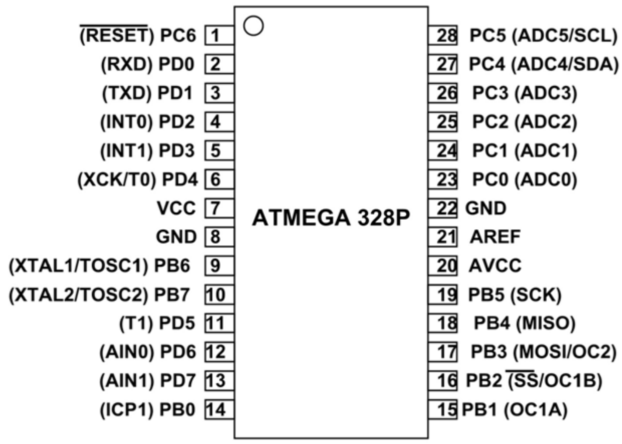

Figure 1. Pin out of ATmega328p microcontroller.

allowed user interaction, a buzzer generated sound alerts during critical conditions, and an LED indicated the status of the water pump. All these electronic components were integrated onto the PCB and enclosed within a wooden box for protection. The complete module was utilized to operate a 1 HP pump at a house.

In this section, the architecture of the proposed automation system, its working principle, the essential calculations involved in the automation process, and the cumulative amount of water consumption are explained.

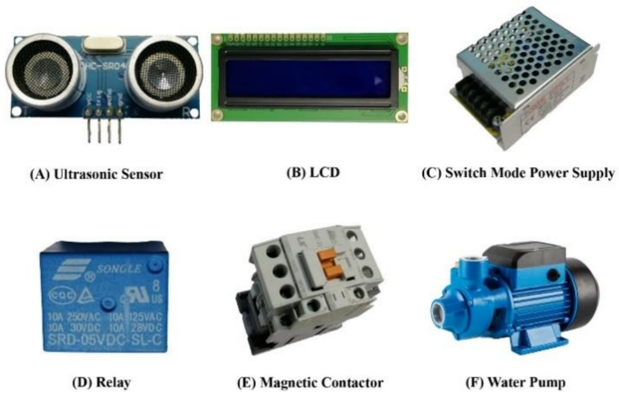

Figure 3. Components used in the development of the proposed automation system. The components include: (A) Ultrasonic sensor HC-SR04 module, (B) 16 × 2 LCD, (C) Switch mode power supply, (d) Relay SRD-05VDC-SL-C, (E) Magnetic contactor, and (F) Water pump.

Proposed Architecture

The proposed system is designed to accommodate various shapes of roof-top water tanks, including cylindrical and rectangular. With this consideration, our system is versatile and compatible with all tank shapes. The block diagram illustrating the proposed architecture is depicted in Figure 4. In this setup, the ultrasonic sensor is positioned at the top of the water tank and connected to the microcontroller using a Cat-4 cable. The sensor continuously detects the water level in the tank and transmits the information to the microcontroller. The push buttons serve two functions: enabling data entry and interrupting the microcontroller to execute specific tasks. The LCD screen provides a user-friendly interface for data entry, displaying the dynamic water level in percentage, pump status (ON or OFF), cumulative water consumption in liters, and relevant messages based on the control algorithm. The light indicator indicates the current status of the pump (ON or OFF). Additionally, a buzzer is employed to sound an alarm at critical points, such as when the pump is activated or deactivated. The pump controller circuit board ensures a seamless and safe connection between the pump and the main power supply. Furthermore, a manual pump operation button is included in the push button array for convenient manual control. Our control algorithm incorporates a preventive mechanism to safeguard the pump against dry-running when the ground reservoir becomes empty or the level of ground water falls during dry seasons.

Working Principle

The ultrasonic sensor module is an ideal choice for non-contact liquid level measurement. It consists of a transmitter, a receiver, and control circuitry. The sensor measures the time duration of signal propagation from the transmitter to the object and back to the receiver to determine the distance between the sensor and the reflecting object. The microcontroller then calculates the distance according to a well-known Equation (1). Figure 5 provides a clear illustration of this water level measurement principle. In this project, the ultrasonic sensor is placed under the lid of the tank to determine the water level. The microcontroller controls the water pump based on the continuous assessment of the water level as follows:

- When the water level of the overhead tank goes down roughly 10% of the tank height, the pump is turned ON automatically.
- When the reservoir gets empty, i.e., dry running of the pump, or the water level of the overhead tank goes higher than or equal to 90% of the tank height, the pump is turned OFF automatically.

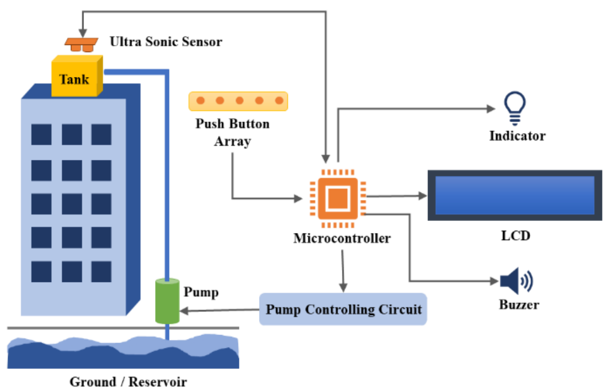

Figure 4. Proposed automatic roof-top water tank filling system architecture.

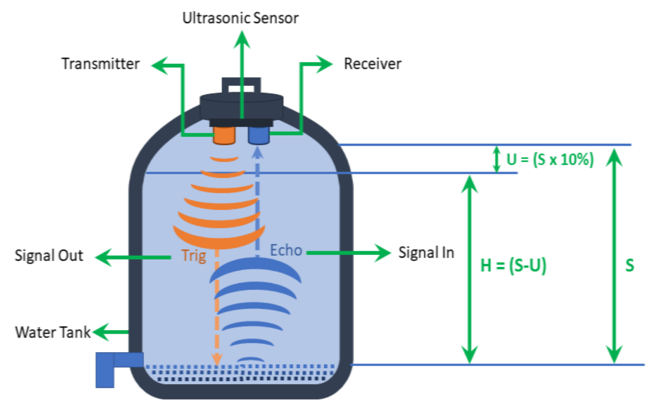

Figure 5. Ultrasonic sensor-based water level measurement principle.

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Calculations of Water Level and Water Consumption

Let's determine the water level in the overhead reservoir. Assume the sonar sensor's distance from the water surface is *S*. The ultrasonic module is programmed that starts an internal timer and measure the time interval until an echo is detected. Meanwhile, the signal travels a 2*S* distance. Ignoring the effect of temperature, the distance from the sensor to the reflecting surface can be calculated using the speed-time-distance relationship as follows:

$$S = \frac{vT}{2} \tag{1}$$

where *T* is the travel time, *v* is the velocity of sound. The measured distance *S* belongs to the height of the water tank. We intend that 10% of the tank should be empty. Here, is the unfilled tank height,

$$U = \; S \times 10\% \tag{2}$$

Therefore, the height up to which the tank should be filled is,

$$H = S - U \tag{3}$$

which is 90% of total height *S*. The water level present in the tank is inverse to the distance S^0 measured by the sensor where S^0 is the dynamic assessment. Therefore, to determine the dynamic water level in the tank, we have to subtract S^0 from the max filled height H, i.e.,

$$L = H - S^0 \tag{4}$$

The percentage of water level is determined as follows,

$$L = \frac{H - S^0}{H} \times 100\% \tag{5}$$

Let, the time taken to fill the cylindrical (V_c) or rectangular-shaped (V_r) tank, be *t*. Therefore, amount of consumed water,

$$C_v = \text{Previous amount of consumption} + \frac{V_c \text{ or } V_r}{t} \times t^0 \tag{6}$$

where $V_c = \pi r^2 H$; $V_r = l \times b \times H$ and t^0 is the active period of the pump counted by the microcontroller at the initial cycle.

Circuit Diagram

The SMPS unit has been shown in Figure 6, supplies 5 Volt DC power to the controlling circuit board. The microcontroller ATmega328p's PB0, PB1, PB2, PB3, PB4, and PB5 pins are connected to the LCD, while the push buttons for MANUAL ON/OFF, CLEAR (which clears the dynamic amount of water consumption and sets it to zero), OK (Confirmation), SET (Data entry), and RESET (Reinstallation) are connected to pins PC0, PC1, PC2, PC3, and PC4, respectively. The other ends of these push buttons are connected to 5V. Pull-down resistors R1, R2, R3, R4, and R5 are connected to the ground to set the digital logic level of pins PC4, PC3, PC2, PC1, and PC0 as default 0 until the push buttons are pressed, and the logic level pins become high to perform the functions according to the algorithm. A buzzer with a 100Ω resistor in series is connected to the microcontroller's PD4 pin. The sonar echo and trig pins are connected to the microcontroller's PD5 and PD6 pins, respectively. Pin PD3 is connected to a relay via a relay driver NPN transistor BD135. To control overvoltage, a relay driver and a diode are used. The relay is connected to switch the magnetic contactor to operate the 220V water pump. Proteus software was used to design and simulate the circuit, and a PCB was finally constructed to assemble all electronic components. A wooden box is used to cover the circuit board while exposing the display unit and fixing the 5 push buttons on top. Figure 6 shows a schematic of the circuit.

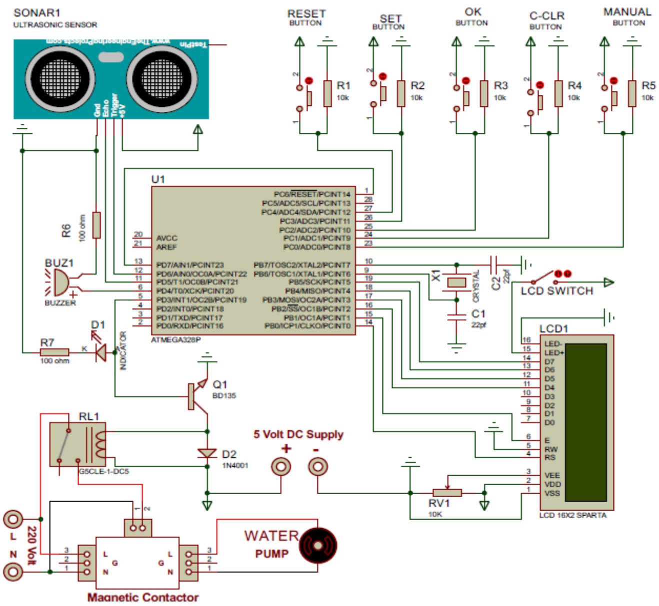

Figure 6. Schematic of water pump controlling circuit board

Controlling Algorithm

The controlling algorithm of the automatic overhead water tank filling system is depicted by a flow diagram in Figure 7. The microcontroller first checks if it has been previously programmed and if so, it proceeds with its routine work. Otherwise, it uses the ultrasonic sensor to determine the height of the water tank and prompts the user to input tank parameters such as shape (cylindrical or rectangular) and dimensions (length, width, or circumference). These parameters are stored in the EEPROM for future reference. During routine work, the microcontroller reads the stored data and checks for any interruptions. If there is an interruption, it performs a predefined task. Otherwise, it continuously calculates the water level using Equations (1 to 5), and displays it as a percentage.

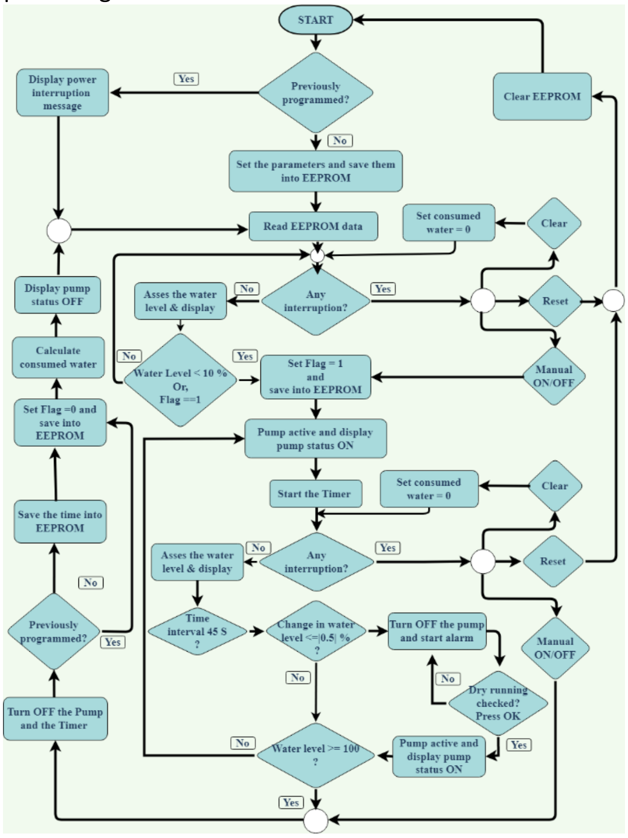

Figure 7. Flow chart of automatic roof-top water tank filling system.

If the water level drops below 10% or the pump stops due to a power outage i.e., flag value is 1, the microcontroller automatically restarts the pump as soon as power is restored, and continues until the tank is full, displaying "ON" status during the pumping action and "OFF" when the pump is stopped. Each activation cycle of the water pump involves setting a flag and timer to track the status and active period of the pump, respectively. The pump is turned off when the water level reaches 100%, with the flag and timer reset to zero, and this information is saved to the EEPROM. To prevent dry running, the microcontroller checks for water level 0.5% changes in 45 seconds interval and issues an alarm, and shuts down the pump if there is no change. The amount of water consumed is calculated using Equation (6), based on the shape of the tank. The initial filling of the tank without any leakage is recorded, and this time period is used to calculate the amount of water for subsequent cycles, which is displayed cumulatively in liters.

Installation and Operational Procedure

The installation process for the overhead water tank filling system is outlined in Figure 8. Prior to installation, the tank must be empty. After displaying introductory and directional messages in steps-1 and 2, respectively, the microcontroller determines the height of the water tank in step-3, which is crucial for accurate pump control and water consumption measurement. The height is then displayed in centimeters automatically. The shape of the water tank is determined in step-4, and the user selects between two options: cylindrical or rectangular. After selecting the tank shape in step-5, the user confirms it in step-6 using the SET and OK buttons. For cylindrical tanks, the user inputs the length and width of the tank, while for rectangular tanks, the user inputs the circumference in step-7. Even if the tank shape is not cylindrical or rectangular, the system can still operate, although it may not provide accurate water consumption readings. The current water level is displayed in the first row of the LCD, while the second row displays the status of the pump and water usage in liters (step-8). Any power interruptions are indicated by the text "Electricity Failure" on display. To reset the water usage to zero, the user can press the CLEAR button. The MANUAL button can be used to turn the pump ON or OFF manually when needed. Pressing the RESET button prepares the system for re-installation, and the text "Resetting...." appears on the LCD.

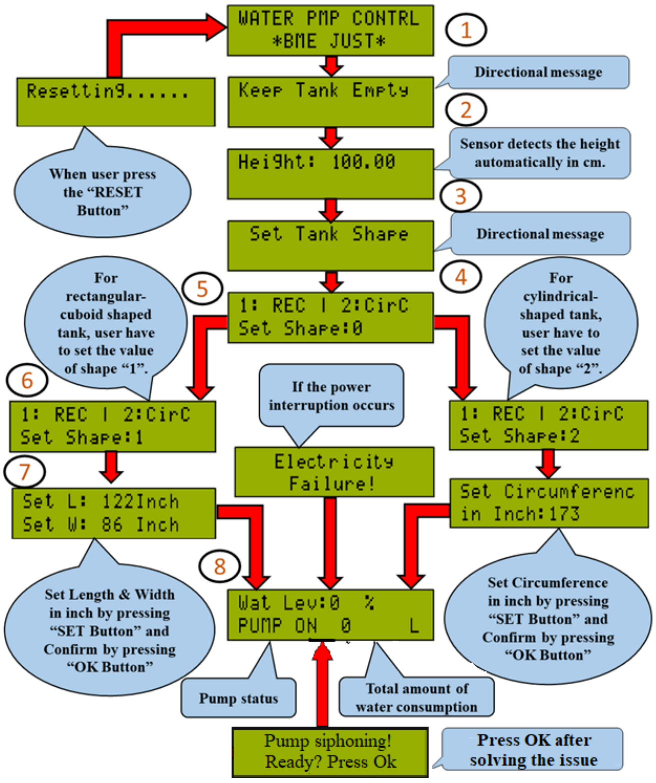

Figure 8. Installation steps for automatic roof-top water tank filling system

Table 1. Features and performance analysis of the automatic roof-top water tank filling system.

Features	Functions	Comments
RSET	System gets ready for reinstallation.	Performed well.
SET	• Specify the shape of the water tank as either rectangular (denoted by "1") or cylindrical (denoted by "2"). • Input the dimensions of the tank, such as length and width for rectangular tanks or circumference for cylindrical tanks, within the range of 1 to 254 inches.	Performed well.
OK	Notify the microcontroller of task completion.	Performed well.
CLEAR	Reset the cumulative water consumption amount to zero	Performed well.
MANUAL	Operate the water pump manually within the water level range of 10% to 100%	Push the button for 2s to reverse the pump status.
Alarm	• Buzzer sound • LED light • Displayed messages on the LCD	"Pump siphoning! Ready? Press ok." Got 3 times false positive alarm.

During the pump activation period, the microcontroller monitors the water level at intervals of 45 seconds. If the water level remains unchanged by more than |0.5|% of tank height, a text alarm is displayed on the screen, accompanied by an audible alert from the buzzer, and the water pump is automatically turned OFF. This indicates a potential dry-running situation, prompting the user to inspect the pump for any issues. To resolve the problem, the user is required to address the dry running concern and initiate pump operation by pressing the OK button. This precautionary measure ensures the protection of the water pump, preventing any undesired damage from occurring.

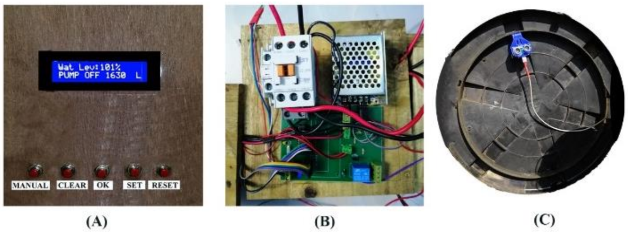

Figure 9. Automatic water tank filling system unit (A) Front side (B) Interior side (C) Sensor attachment.

Results and Discussion

In a real-world scenario, we implemented our designed and developed system to fill a 2000-liter water tank situated on the roof of a duplex house. Figure 9 showcases the front side of the operating controller board, the interior side, and the position of the sensor attachment. For this purpose, a 1 HP motor was employed to pump water from the ground into the rooftop tank. Over a span of more than a month, we closely monitored the system's performance and tracked the dynamic amount of consumed water.

In order to evaluate the effectiveness of our developed system, we gathered feedback from the residents of the house regarding its features and the performance of the water pump controller as presented in Table 1. Overall, they expressed satisfaction with the system's performance, with one exception pertaining to the safety feature related to the dry running of the pump. During the observation period, there were three instances where the safety feature triggered a false positive alarm. These occurrences were attributed to simultaneous water usage by the residents while the water pump was operating. As a result of the inflow and outflow rates were approximately the same, and the water level did not change within the designated time limit of 45 seconds. Consequently, a false alarm was issued and sounded. However, this issue can be easily resolved as the controller automatically stops the pump in such situations. Subsequently, the pump could be manually started by checking for any safety concerns. Furthermore, there existed a potential risk of water droplets causing interference with the sensor while the tank was being filled, particularly as it approached its full capacity. This interference had the potential to result in inaccurate readings and the generation of misleading information.

Conclusion

The automatic water tank filling system has been successfully implemented, offering energy conservation and preventing water spillage. It provides convenient home use, ensuring sufficient water levels even during peak hours. The system saves manual labor, time, and offers real-time updates of water levels in the rooftop tank. It accurately displays water usage and supports water consumption analysis for billing purposes. These efforts demonstrate our dedication to advancing and developing complex initiatives in this field. In the future, we aim to enhance our work by developing an app-based automated system that offers comprehensive status notifications and allows pump control via smartphones. Furthermore, we will explore efficient methods to prevent pump free running and safeguard the sensor from being affected by water droplets.

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