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DESIGN AND IMPLEMENTATION OF A MOBILE SOLAR-POWERED, CONTACT-LESS HAND-WASHING MACHINE FOR IMPROVED HYGIENE IN RURAL COMMUNITIES

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Abstract - This project focuses on the design, construction, and testing of an automatic solar-powered contactless hand-washing machine. The system was designed to provide an efficient and hygienic solution for handwashing without the need for physical contact, thereby minimizing the spread of germs. The construction involved integrating a solar-powered system with automatic sensors that dispense water and soap upon detecting a user's hands. The machine was designed using locally available materials to ensure sustainability and cost-effectiveness. To validate the performance and reliability of the system, the constructed machine was tested by fifteen (15) different individuals per day over a period of ten (10) days, at various times to simulate diverse user conditions. Throughout these tests, the machine demonstrated consistent performance, with all components functioning correctly and achieving a 100% efficiency rate. However, considering a tolerance of ±5% to account for potential system imperfections such as minor sensor delays or variations in solar power availability, the operational efficiency could realistically be considered to be around 95%. These results indicate that the solar-powered contact-less hand-washing machine is highly effective and reliable, achieving the primary objective of providing a sustainable, hygienic, and autonomous solution for hand hygiene. The project successfully met its aim of designing and constructing an efficient Automatic solar-powered hand-washing system that can operate effectively in varying conditions.

Keywords - Hand-washing machine, Solar-powered, Contact-less, Ultrasonic sensor Microcontroller, Hygiene

1. Introduction

The importance of effective hand hygiene, particularly in preventing the spread of communicable diseases, has been well-documented. hand-washing with soap and water is one of the most effective ways to prevent disease transmission (World Health Organization, 2020). However, in rural communities, limited access to clean water, soap, and electricity poses significant challenges to maintaining proper hygiene standards (UNICEF, 2021). This issue has become even more pressing due to global health challenges such as the COVID-19 pandemic, which highlighted the critical role of hand hygiene in infection control (Centers for Disease Control and Prevention, 2020).

Technological interventions can provide innovative solutions to these barriers. One such approach is the development of solar-powered, contactless handwashing systems. Solar power offers a sustainable energy source for off-grid locations, while contactless mechanisms minimize the risk of cross-contamination, improving hygiene standards (Kouadio et al., 2022). This paper presents the design and implementation of a Mobile Solar-Powered, Contactless Hand-Washing Machine, tailored specifically to rural communities. The mobility feature ensures that the system can be easily relocated, allowing it to serve dispersed populations more effectively (Adebayo & Umar, 2023).

By leveraging solar energy and contactless technology, this machine provides a cost-effective and sustainable solution for improving public health in resource-constrained environments, as demonstrated in several case studies (Abebe&Tesfaye, 2021).

2. Literature Review

Access to clean water, effective sanitation, and hygiene (WASH) infrastructure is crucial for preventing the spread of infectious diseases, particularly in rural areas. Rural communities often face significant barriers, such as a lack of clean water, inadequate sanitation facilities, and limited access to electricity (UNICEF, 2021). These challenges necessitate innovative solutions, particularly in light of global health crises like the COVID-19 pandemic, where hand hygiene has been shown to be an effective measure for infection control (World Health Organization [WHO], 2020). Solar-powered, contactless handwashing systems have emerged as a promising solution to these problems.

Handwashing with soap and water is a proven and effective way to prevent disease transmission, especially in resource-poor settings (CDC, 2020). In low-income, rural areas, where sanitation is often inadequate, the lack of clean water and soap has been associated with higher incidences of communicable diseases such as diarrhea, respiratory infections, and skin conditions (Curtis et al., 2011). However, many rural areas have limited hand-washing facilities, which underscores the need for innovative, accessible hand-washing solutions (UNICEF, 2021).

Solar energy is a sustainable, renewable resource with immense potential to address the energy gap in rural areas. Since many rural areas in developing countries are not connected to the national grid, solar-powered systems have been increasingly adopted to meet the energy needs of these communities (Khan et al., 2018). Solar-powered water systems have been used to provide drinking water, irrigation, and even sanitation in regions where conventional power supply is either unreliable or non-existent (Adebayo & Umar, 2023). Applying solar technology for handwashing systems provides a cost-effective and sustainable solution for hygiene in off-grid rural areas.

Contactless hand-washing technology has gained prominence as a solution for minimizing the risk of contamination in communal facilities. The use of sensors to automate water and soap dispensing prevents users from physically touching surfaces, which could potentially harbor pathogens (Kouadio et al., 2022). Contactless systems have been shown to reduce the spread of infections, especially in high-traffic areas, and their implementation in rural health settings could greatly improve public health outcomes (Nkengasong&Tessema, 2020). This is particularly relevant during pandemics like COVID-19, where minimizing touch points is critical to preventing virus transmission (Rodriguez et al., 2020).

Mobility is a key consideration in rural communities, where populations may be dispersed and access to centralized handwashing facilities is limited (Adewumi et al., 2020) or even does not exist. The development of mobile handwashing stations enables these systems to reach more people, including those in remote areas. A mobile solar-powered, contactless hand-washing machine combines sustainability, convenience, and accessibility, making it ideal for rural settings where infrastructure is lacking (Abebe &Tesfaye, 2021). Mobile systems can be moved to different locations as needed, such as markets, schools, and clinics, further enhancing the potential for improved hygiene practices (Adebayo & Umar, 2023).

Several solar-powered hand-washing solutions have been developed and deployed in rural areas, with varying degrees of success. For example, in Kenya, a solar-powered, contactless hand-washing system was introduced in rural health centers, leading to a significant reduction in cross-contamination and improved hygiene compliance (Omondi et al., 2021). However, the need for mobile systems remains underexplored. Current hand-washing solutions are often fixed in place, limiting their reach and flexibility (Adewumi et al., 2020). The gap in the literature highlights the importance of developing mobile, sustainable hand-washing systems that can be deployed in diverse rural settings to further enhance hygiene and health outcomes.

3. System Design

There are four key elements involved in the design, they include; solar energy generation, water pumping, soap dispensing, and sensors for the contactless mechanism.

The Solar Energy Generation

The solar power system will power the pump, sensors, and control system requiring the components; solar panels, battery for energy storage, and charge controller. The design considerations are as follows;

The total power consumption is given by Equation 1.

$$P_T = P_p + P_C + P_S + P_M \qquad (1)$$

Where, P_p is the power consumed by the water pump, P_C is the power consumed by the control unit, P_s is the power consumed by the sensors, P_M is the power consumed by any additional components (e.g., soap dispenser). For the system to operate for a period of t_h per day, the total energy required per day will be;

$$E_d = P_t \times t_h \text{ (watts} - \text{hours)} \qquad (2)$$

To calculate the required solar panel output assuming that I_{Solar} is the average sunlight hours available per day, the solar panel power, P_{solar} should satisfy equation 3.

$$P_{solar} \times I_{Solar} \geq E_d \qquad (3)$$

Thus, the minimum power rating of the solar panel is:

$$P_{solar} \geq \frac{E_d}{I_{Solar}} \qquad (4)$$

Battery Sizing

A battery is needed for storing energy to run the machine during periods without sunlight. The battery capacity, C_b in Ampere-hours (Ah) is given by equation 5.

$$C_b = \frac{E_d}{V_b} \qquad (5)$$

where V_b is the battery voltage.

The powering section for this design contains a 12v/7.2AH battery, 20watts solar module, and 10A charge controller.

Water Pump System Design

The water pump should be able to deliver a certain flow rate and pressure to provide sufficient water for handwashing. The design process is as follows;

Flow Rate Calculation:

The volume of water per cycle is given by equation 6.

$$V_{wash} = Q \times t_{wash} \qquad (6)$$

Where, Q is the required flow rate (in liters per second or gallons per minute) and t_{wash} is the time for one hand-washing cycle (in seconds).

The water tank is sized accordingly by equation 7.

$$V_{tank} = V_{wash} \times N_{cycle} \qquad (7)$$

Where V_{tank} is the total tank capacity and V_{cycle} is the number of wash cycles.

Pump Power

The pump power P_P is estimated using equation 8.

$$P_P = \frac{\rho \times g \times h \times Q}{\eta_{pump}} \qquad (8)$$

Where ρ is the density of water (1000 kg/m³), g is the acceleration due to gravity (9.81 m/s²), h is the height the water is pumped and η_{pump} is the efficiency of the pump.

For small-scale applications like a hand-washing machine, typically, the flow rate is between 1 and 3 liters per minute (L/min), the height is 1 to 3 meters and the Power rating of a direct current (DC) submersible pump in this category generally consume 5 to 30 watts. For this project, it was assumed that the flow rate, $Q = 2\ \text{L/min} = \frac{\frac{2}{1000}}{60}\ \text{m}^3/\text{s}$, height $h = 2$ m, and efficiency, η_{pump} is 60%. From equation 8, the power consumption of the pump, $P_P \approx 1.09$ W. This is the hydraulic power required. The actual electrical power consumed by the pump was assumed to be 3W which should be higher than the calculated value to take care of the losses in the motor and other inefficiencies.

Contactless Operation Design (Sensor System)

The contactless operation is enabled by proximity or motion sensors (e.g., infrared or ultrasonic sensors). The sensor power consumption P_S can be modeled by equation 9.

$$P_S = I_S \times V_S \qquad (9)$$

Where I_S is the sensor's current and V_S is the voltage ratings. For the design in this paper, the contactless operational section contains two ultrasonic sensors - one for water hand-washing sensing, and the other for soap hand sensing. The sensor contains two ultrasonic wave triggering and receiving components called "trigger" and "echo". The echo components echo an inaudible sound that can travel a maximum of 400cm (4m). The trigger component receives the sound at any distance with which the sound meets an obstacle. The distance of the obstruction is calculated by the microcontroller and the processed distance is used to perform the pumping instructions and vice versa.

The soap dispenser was powered similarly to the water pump. For simplicity, it was assumed that the same mathematical model for the pump applies to the soap dispensing system, with little adjustment for the different viscosity and flow requirements. For the design in this paper, the soap and water dispensing mechanism was such that a water sink was constructed to collect both water and soap liquid. A hand-washing tap was mounted in front of both sensors such that when the sensors sense a hand under water or soap tap, it sends the signal to the microcontroller which in turn switches the water or soap dispenser pump as the case may be. The distance at which the water contactless sensor sees the hand and trigger water dispensing is 20cm, while the soap counterpart is 15cm. This difference in distance positioning is to ensure that both sensors do not react at the same time upon sensing one's hand. The water supply section of the prototype design contains a 10-liter transparent bucket. The pumping system is a DC submersible water pump, with a hose and pipe which creates a passageway for water to flow during dispensing.

4.0 System Block and Circuit Diagrams

The block diagram of the system is shown in Figure 1. The ultrasonic sensor sends a signal to the microcontroller, which processes the information and activates the water pump, LED, and buzzer through relays. The system is powered by a solar module and battery, ensuring continuous operation.

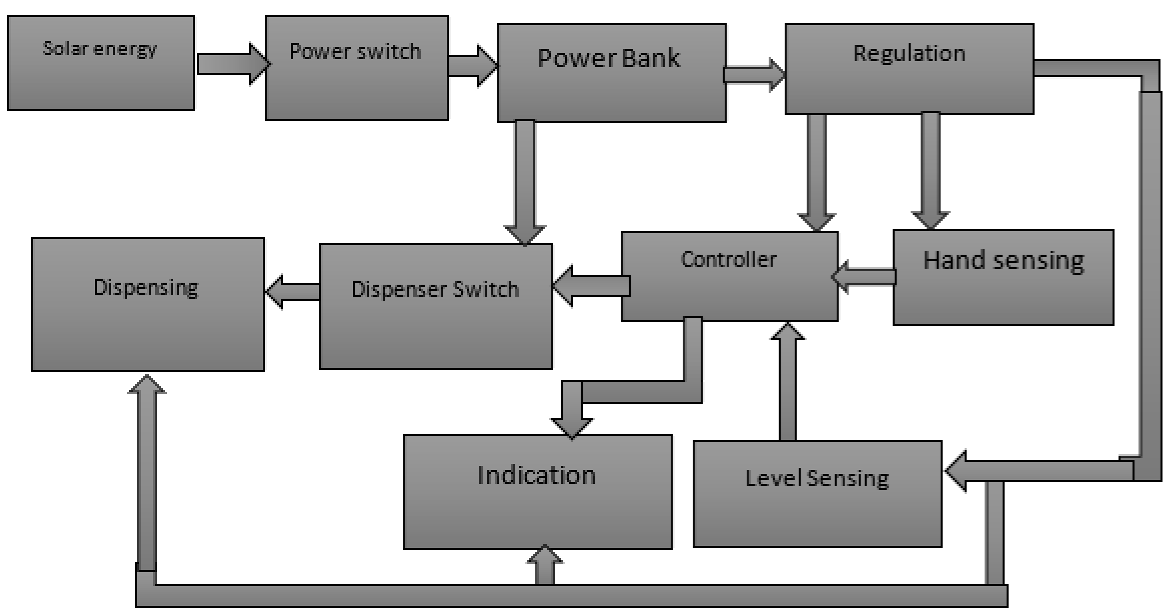

Figure1: Block diagram of the Solar-Powered, Contact-less Hand-Washing Machine

From Figure 1, the power supply supplies electrical energy to the entire circuit components through the power switch. When the supply goes through the power switch, it then flows into the power bank block for energy storage. The power bank stores the energy obtained from the sun for use during bad weather or during the night. This energy regulation block contains the functionality of the project that ensures power regulation for the controller, sensors, and indicator components, including the dispensing block. After the regulation, the regulated energy flows into the control, hand sensing, level sensing, and the dispensing block as indicated. When the regulated energy enters the system, its brain box (the controller) gets activated and at this point, it begins to collect data from the level sensing and the hand sensing blocks. The level sensing block represents the part that checks for the availability of the soap and water to tell the controller whether to dispense the soap or not. Again, the hand sensing block tells the controller that someone has positioned his/her hand(s) for soap or water dispensing; and if the status of the level sensing block as may be read by the controller is positive, it instructs the dispensing block through the dispensing switch to release soap or water to the person as the case may be. But if the status is negative as may be read by the controller as well, the controller avoids turning ON the dispenser as there will be nothing to dispense, and hence, the controller triggers an alarm through the indication block. The indication block helps in communicating with the user to share information relative to the operation of the automatic solar-powered contactless hand washing system.

The circuit diagram for each block of the system was developed step-by-step to ensure accurate operation and integration of all components. The circuit diagram of the system is shown in Figure 2.

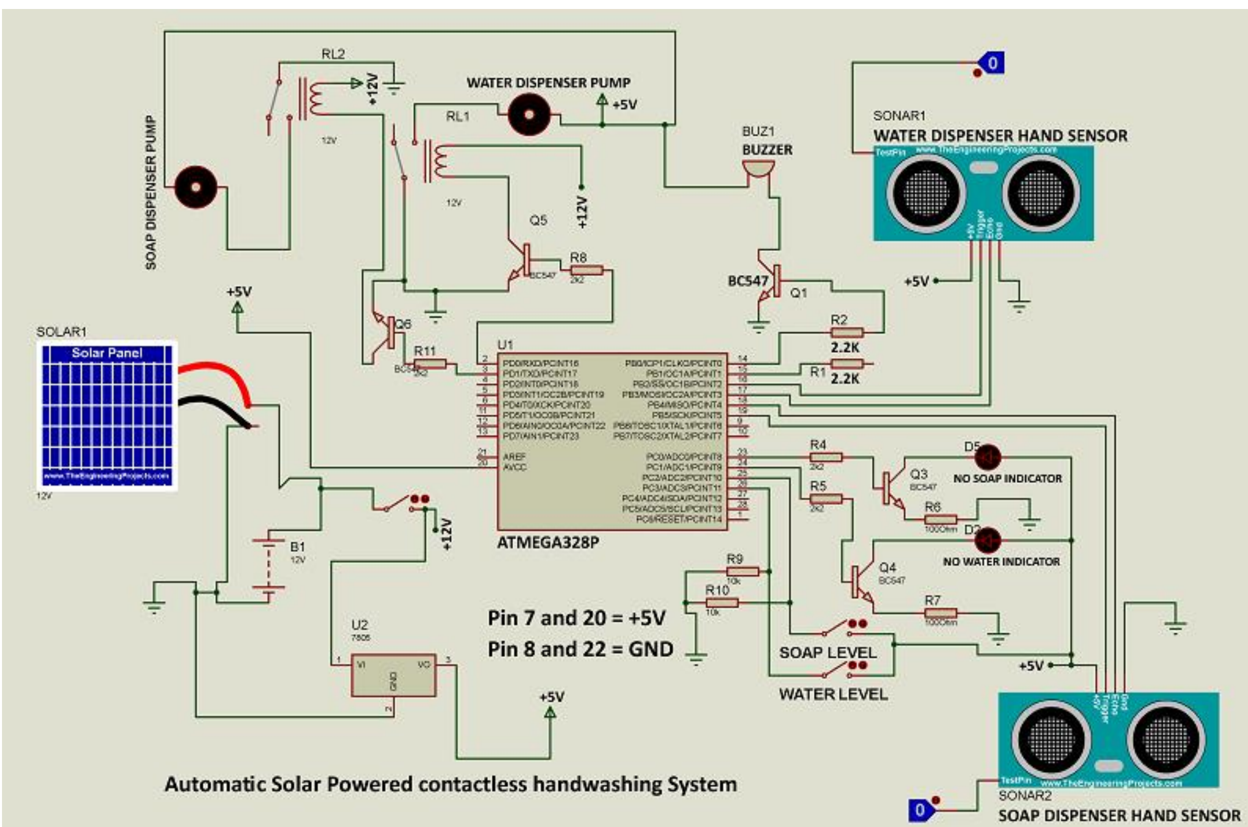

Figure 2: Circuit diagram of the Solar-Powered, Contact-less Hand-Washing Machine

On powering the system, the 12V from the battery goes direct to the Relay (RL1) whereas the other circuit components get their required +5V supply voltage through the output pins of the U2 (7805) voltage regulator component. The "7805" voltage regulator will produce a maximum of 1A at the output-regulated voltage pin. When the whole circuit components are powered, the ultrasonic sensors (Hand sensor) and the level sensor begin to search for the availability of liquid soap, water, and the presence of a human hand respectively. When the hand sensor detects the presence of a human hand, it sends the status of the detected signal to the microcontroller for processing. The microcontroller processes the detected signal and calculates the distance of the detected object from the system, if the distance is far from the system in such a way that the soap or water liquid will spill without falling on the detected object, the controller will not instruct the dispenser for dispensing. If the distance is close enough that when dispensing, the soap or water liquid will spill on the detected object, then the controller further reads the status of the soap and water level sensor, processes and calculates the depth of the soap and water container to determine the availability of the soap and water. If the depth is the same as the depth of the container, it means the container is empty and contains no soap or water at that moment; and if the dispenser is allowed to run in this condition, it will be burnt so, the controller will not switch "on" the soap or water dispenser depending on which of the dispensers is being placed hand under, pending when there is enough soap or water to cover the dispenser. At this point, it triggers the buzzer and the warning LED through R1, R2, Q1, and Q2 respectively which then beeps the buzzer alarm and flashes the warning LED as an indication that there is no soap sanitizing liquid. Furthermore, if the depth of the container as read by the level sensor is small or shorter than the depth of the container, then the controller turns "on" the dispenser through the R8, Q5, and RL1. The work of the R8 (2.2K resistor) is to bias/activate the NPN transistor (Q5 – BC547). When the transistor is biased, it picks the ground signal and completes the Relay circuit (RL1). When the relay gets the ground signal through the collector of the BC547, having connected one of its coils to the positive of the battery, the relay will switch "on". This action of the relay will move the 'COM' terminal to the 'NO' thereby connecting the ground (GND) signal with its full current to the cold end of the dispenser PUMP. When this happens, the dispenser turns "on" and begins to send out the soap or water through its connected hose/pipe. The LEDs 'LOW Level and ENOUGH soap or water indicators respectively will light up in response to the level of the soap and water available in the container. When the soap or water is below the half level of the container, the 'Low level' indicator lights up but if the soap or water is above the half level of the container, then the 'Enough level' indicator will light up. Finally, the LCD module digitally displays text information about everything happening in the system. It shows when a hand is detected and liquid (either soap or water) is dispensing, displaying the status of the dispenser as either running or stopped. The instruction(s) sent to the switching components and the indication components are embedded in the memory of the Atmega328P microcontroller IC. These instructions are written in embedded C language using Arduino integrated Development Environment (Arduino IDE).

4. System Implementation and Testing

The solar panel and battery charging circuit were temporarily set up on the breadboard. The solar panel was placed under a light source to simulate charging, and the output was monitored to ensure proper charging of the battery. The battery was then used to power the entire breadboard circuit.

The ultrasonic sensor was connected to the breadboard along with the microcontroller. The sensor's VCC and GND pins were connected to the power rails on the breadboard of Figure 3, while the trigger and echo pins were connected to the designated digital pins on the microcontroller. The sensor was positioned to detect the presence of hands placed in its range. The microcontroller was set up to receive signals from the ultrasonic sensor and process them accordingly. Connections were made from the microcontroller to the LED, buzzer, and relay modules. Test code was uploaded to the microcontroller to ensure that the sensor's detection would trigger the relay, LED, and buzzer appropriately.

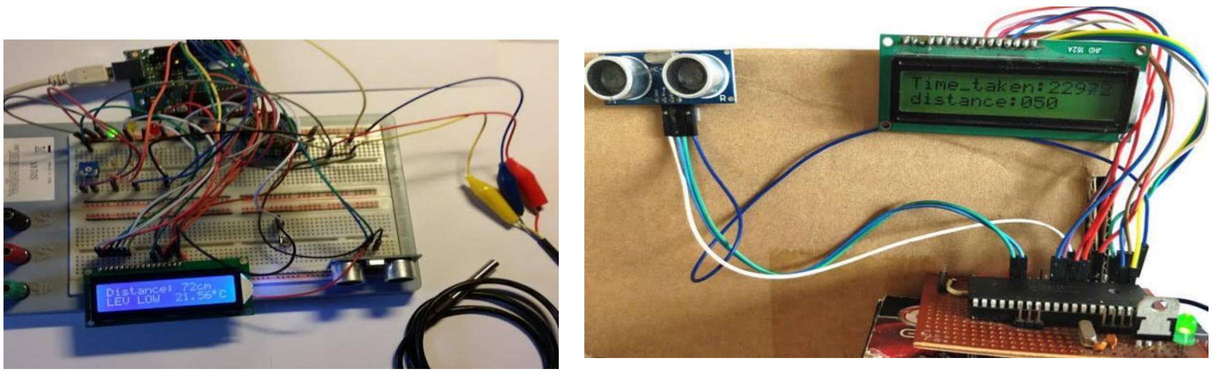

Figure 3: Circuit implementation

The completed Vero-board circuit was powered and tested to confirm functionality. Several adjustments were made to optimize the circuit, including repositioning components and adding additional resistors where necessary to regulate voltage and current. The water pump was tested under different conditions to ensure consistent operation. The final assembly involved integrating all the units into a cohesive system that could be enclosed in a protective casing. To ensure durability, ease of maintenance, and aesthetic appeal, a metal casing with screws were used and the electronic circuits were well-fitted inside the metal casing. All wiring was routed neatly inside the enclosure to avoid any short circuits or interference with the sensor. Additional insulation was used where necessary to prevent electrical shock. The solar panel was neatly mounted on top of the enclosure as shown in Figure 3. Wiring was run from the panel through waterproof grommets to the inside of the casing. The implemented system during implementation and under test is shown in Figure 3.

Figure 3: System Implementation and Testing

The system testing included testing the sensor's range and sensitivity, verifying the water flow rate, checking the LED indicators and buzzer, and ensuring that the solar charging system was operational. Minor calibrations were made to adjust the sensor range and pump activation timing. The product was tested by fifteen (15) different persons per day for ten (10) days at different times and the system worked in all cases meaning that the system has shown 100% efficiency. Considering a tolerance of ±5% for system imperfection, the overall efficiency is 95%.

5. Conclusion

The design and construction of a Mobile Solar-Powered Contactless Hand-Washing Machine has been presented to address the need for an accessible, sustainable, and hygienic hand-washing solution in rural communities. The machine's solar-powered operation and contactless functionality reduce the risk of cross-contamination while promoting water and energy conservation. The findings confirm that such innovative solutions are feasible and practical, particularly in settings with limited infrastructure. Overall, the paper highlights the importance of integrating sustainable practices with public health initiatives to enhance the well-being of rural dwellers.

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