DESIGN AND DEVELOPMENT OF A SOLAR-POWERED AQUATIC WASTE COLLECTION SYSTEM USING ESP32-BASED WIRELESS CONTROL

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Abstract -*Water pollution caused by floating solid waste such as plastics and organic debris has become a major environmental issue affecting aquatic ecosystems. This paper presents the design and development of a solar-powered aquatic waste collection system that efficiently removes floating waste from water bodies like lakes, rivers, and canals. The system operates using solar energy, making it environmentally friendly and cost-effective. It consists of a floating platform integrated with solar panels, a battery storage system, DC motors, a conveyor mechanism, and a wireless control system based on ESP32 microcontrollers. The collected waste is transferred into a storage bin using a conveyor belt mechanism. The system can be operated remotely using a joystick-based control unit via ESP-NOW communication. The proposed system reduces human effort, ensures safe operation in polluted environments, and contributes to sustainable waste management. The prototype demonstrates an effective and practical solution for maintaining clean water bodies.*

Key Words: **Solar Energy, Aquatic Pollution, Waste Collection System, ESP32, Conveyor System, Renewable Energy, Water Cleaning**

1.INTRODUCTION

Water pollution due to floating solid waste has become a significant environmental and engineering challenge, particularly in urban and semi-urban water bodies such as rivers, lakes, canals, and drainage systems. The continuous accumulation of non-biodegradable materials, especially plastics, leads to severe ecological degradation, including reduction in dissolved oxygen (DO) levels, obstruction of sunlight penetration, and disruption of aquatic food chains. Conventional waste removal techniques primarily rely on manual cleaning or fuel-powered mechanical systems, which are inefficient, labor-intensive, and associated with high operational costs and environmental risks. Furthermore, existing large-scale aquatic cleaning systems are often unsuitable for confined or shallow water bodies due to limitations in maneuverability, scalability, and energy efficiency. These challenges necessitate the development of compact, energy-efficient, and automated solutions for real-time aquatic waste management.

In this context, the proposed solar-powered aquatic waste collector integrates renewable energy systems with embedded control and electromechanical mechanisms to achieve efficient waste removal. The system utilizes a photovoltaic (PV) module coupled with a charge controller and battery storage unit to ensure uninterrupted power supply under varying environmental conditions. An embedded microcontroller (ESP32) is employed for system control, enabling wireless communication and real-time navigation using a joystick interface via low-latency protocols. The propulsion system, driven by DC/BLDC motors, facilitates movement across the water surface, while a conveyor-based collection mechanism ensures continuous removal and transfer of floating debris into a storage unit. The integration of power electronics components such as DC-DC converters and motor drivers enhances energy optimization and system reliability. This approach offers a sustainable, low-cost, and scalable solution for aquatic pollution control, aligning with modern environmental engineering practices and smart water management systems. The novelty of this work lies in the integration of solar energy with a compact, low-cost conveyor-based aquatic cleaning system using ESP-NOW communication.

2. LITERATURE SURVEY

Recent research on aquatic waste management focuses on automated systems for efficient removal of floating debris. S. S. et al. [1] proposed a microcontroller-based marine cleaning system integrated with sensors and solar energy for monitoring and waste collection. Although effective, the system is complex and costly for small-scale applications. A. Akib et al. [2] developed a floating waste collector robot using DC motors and a conveyor mechanism controlled via Bluetooth. Similarly, M. R. Ruman et al. [3] introduced an automated surface cleaning system with remote control and GSM-based monitoring. These systems improve efficiency but rely on conventional battery power, limiting continuous operation. S. H. Y. S. Abdullah et al. [4] designed a portable trash collector boat for small water bodies with a conveyor mechanism and remote navigation. However, the absence of renewable energy integration increases operational cost. Based on these studies, there is a need for a cost-effective and energy-efficient system.

The proposed solar-powered aquatic waste collection system addresses this gap by integrating photovoltaic energy with waste collection mechanisms.

3. SYSTEM DESCRIPTION

The proposed solar-powered aquatic trash collector is an integrated electromechanical system designed for efficient removal of floating waste from water bodies using renewable energy. The system comprises a floating platform equipped with a photovoltaic (PV) module, charge controller, battery storage unit, embedded control system based on an ESP32 microcontroller, propulsion unit using DC/BLDC motors, and a conveyor-based waste collection mechanism. The solar panel converts solar energy into electrical energy, which is regulated and stored in the battery to ensure continuous operation, while power electronic components such as DC-DC converters and motor drivers provide efficient power management and system stability. The ESP32 microcontroller enables real-time control, navigation, and wireless communication using low-latency protocols such as ESP-NOW, allowing joystick-based remote operation. As the system moves across the water surface, the conveyor mechanism collects floating debris and transfers it into a storage container.

4. METHODOLOGY

The working of the solar-powered aquatic trash collector is based on the coordinated operation of power generation, energy storage, control, and mechanical subsystems, as illustrated in the block diagram(fig.1)

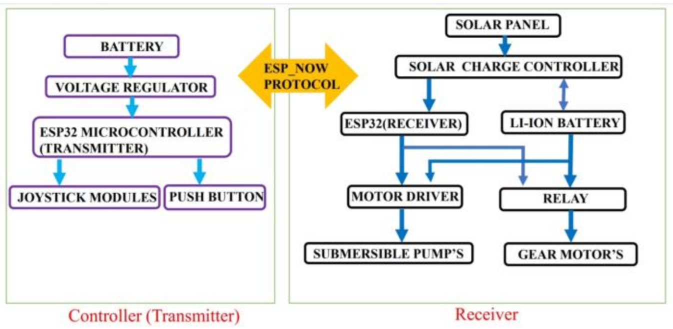

Fig -1: Block Diagram

The photovoltaic (PV) panel converts incident solar radiation into electrical energy, which is regulated by a charge controller to maintain proper voltage levels and prevent overcharging or deep discharge of the battery. The regulated energy is stored in a rechargeable battery, ensuring continuous power supply even during low solar irradiance conditions. The stored electrical energy is then supplied to the embedded control unit, implemented using an ESP32 microcontroller, which acts as the central processing and control element of the system. The ESP32 receives input commands from a joystick-based remote controller via low-latency wireless communication (ESP-NOW protocol), enabling real-time navigation and operation. Based on the control signals, the microcontroller generates appropriate control outputs to the motor driver circuits, which amplify and regulate the signals to drive the propulsion motors (DC/BLDC) and the conveyor motor. The propulsion system enables directional movement of the floating platform across the water surface, while the conveyor mechanism continuously collects floating debris and lifts it into a storage bin.

5. ELECTRICAL DESIGN

5.1 Load Estimation

The approximate power consumption of each component is given below:

Component	Voltage	Current	Power
ESP32	3.3 V	0.15 A	0.5 W
Motor Driver	12 V	0.1 A	1.2 W
Water Pump Motors (2)	12 V	0.3 A each	7.2 W
Gear Motor (2)	9 V	0.2 A each	3.6 W
2-Channel Relay Module	12 V	0.08 A	1.0 W

$$P_{total} = 0.5+1.2+7.2+3.6+1.0 = 13.5W$$

Thus, the total power requirement of the system is approximately:

$$P_{total} \approx 14\ W$$

Solar Panel Selection:

A solar panel of rating 15 Wp (Watt-peak) is selected:

$P_{max} = 15\ W$

Assuming open-circuit voltage:

$V_{oc} = 22\ V$

Maximum power point voltage:

$V_{mp} = 0.82 \times 22 = 18\ V$

Maximum power point current:

$I_{mp} = P_{max} / V_{mp} = 15/18 \approx 0.83\ A$

Energy Requirement:

Assuming operation for 2 hours/day

$E_{required} = 14 \times 2 = 28\ Wh$

Solar Energy Generation:

Assuming 5 hours sunlight/day:

$E_{solar} = 15 \times 5 = 75\ Wh$

Considering 20% losses:

$E_{usable} = 0.8 \times 75 = 60Wh$

COMPONENTS	SPECIFICATIONS/ MODEL
Solar Panel	10 W, 12 V
Solar Charge Controller	12 V ,10 A
ESP32	Dev Module
Battery	12 V, 2600 mah
Gear Motor	9 V, 200 rpm
Bldc Submersible Pump	QR30E, 12 V
Joystick Module	Hw-504
Motor Driver	L298N
Relay	2 Channel
Buck Converter	LM2596

Table -1: Components & Specification

Conclusion of Design:

E_{usable} (60Wh) > $E_{required}$(28Wh)

Thus, the 15 W solar panel is sufficient and more reliable for the system.

5.2 Transmitter

The transmitter section of the system is designed to enable real-time wireless control of the aquatic trash collector using an ESP32 microcontroller. The control interface consists of two dedicated joystick modules and a push-button switch.

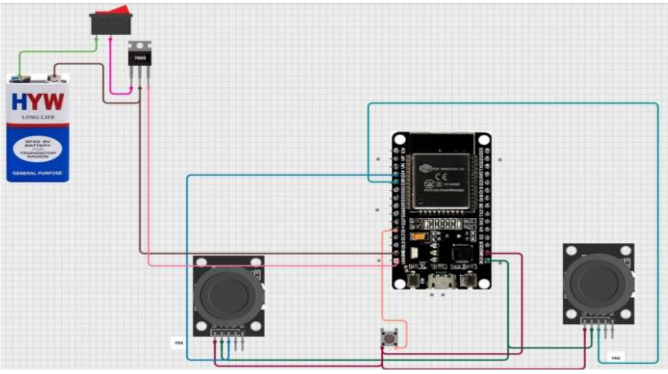

Fig -2: Transmitter Circuit Diagram

The joystick modules generate analog signals corresponding to user inputs, which are processed by the ESP32 through its built-in Analog-to-Digital Converter (ADC). These two joysticks are used to independently control the speed and direction of the propulsion system by varying the input signals to the individual water pump motors, thereby enabling precise forward movement and directional control of the floating structure. In addition, a dedicated push-button switch is used to control the operation of the conveyor belt mechanism, allowing the user to switch the waste collection system ON and OFF as required. The processed control signals are transmitted wirelessly to the receiver unit using the ESP-NOW communication protocol, ensuring low-latency and reliable data transfer.

5.3 Receiver

In the receiver circuit, the propulsion system using water pump motors is controlled through a motor driver module, which regulates the speed and direction by varying the input control signals from the ESP32 microcontroller. This allows precise movement and maneuverability of the floating structure. The conveyor mechanism is operated using a gear motor, which is controlled via a relay module to enable simple ON/OFF switching based on received commands. A DC-DC buck converter is incorporated in the system to step down the 12 V battery supply to the required voltage level suitable for the gear motor and other low-voltage components, ensuring stable and efficient operation.

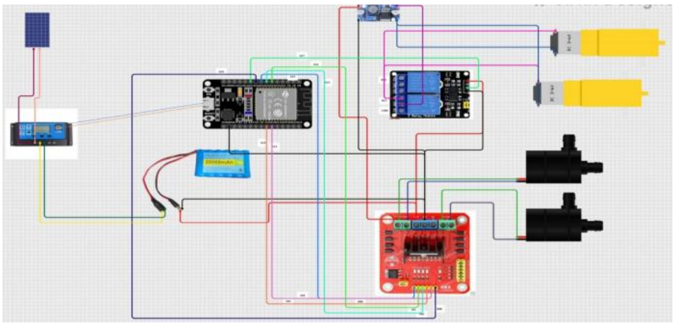

Fig -3: Receiver Circuit Diagram

6. MECHANICAL MODEL

The development of the 3D prototype model of the solar-powered aquatic trash collector is carried out using Tinkercad as the design platform. The model illustrates the structural configuration and functional integration of the system components in a simplified and visualized manner. The design focuses on the arrangement and placement of key elements such as the photovoltaic (PV) panel, floating body frame, propulsion system, and conveyor belt mechanism for waste collection. This virtual prototype aids in understanding the spatial alignment, component interaction, and overall system architecture before physical implementation. The 3D representation of the proposed model is depicted in the following figures.

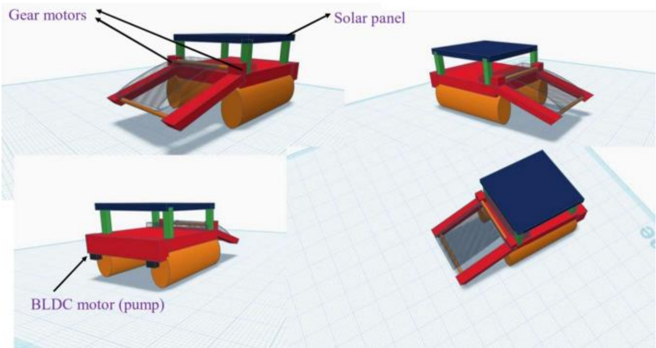

Fig -4: 3D Prototype

6. SOFTWARE SETUP

The software architecture of the system is based on embedded programming using the ESP32 microcontrollers, incorporating the ESP-NOW communication protocol for efficient wireless data transmission between the transmitter and receiver units. ESP-NOW is a low-latency, peer-to-peer communication protocol that operates using the built-in Wi-Fi hardware of the ESP32, offering advantages such as reduced power consumption, faster data transfer, and extended communication range compared to conventional Bluetooth-based systems. The communication between the two ESP32 modules is established using their unique MAC addresses, eliminating the need for a traditional network infrastructure. Both ESP32 units are programmed in embedded C to ensure real-time control and efficient system operation.

In the transmitter unit, the program is designed to read analog inputs from the joystick modules and a digital input from a push-button switch. The joystick inputs corresponding to the X and Y axes are processed through the ADC channels of the ESP32 and mapped into binary control signals (1 or 0) based on predefined threshold values, enabling directional control of the system. The push-button input is used to toggle the operation of the conveyor mechanism between ON and OFF states. The processed data is structured into a defined data packet (struct message) and transmitted to the receiver ESP32 using the ESP-NOW protocol. A callback function is implemented to confirm successful data transmission, with an LED indicator providing visual feedback of the communication status. Small programmed delays are included to regulate the transmission frequency and ensure stable communication.

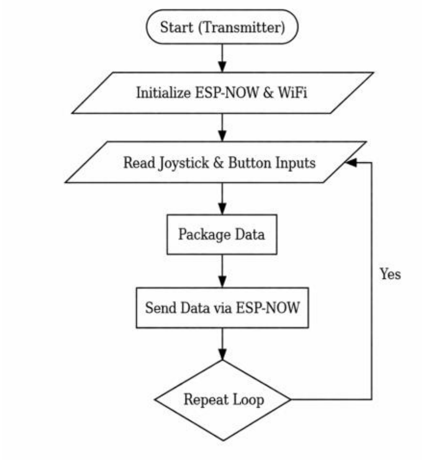

Fig -5: Flowchart of Transmitter ESP32

On the receiver side, the ESP32 is configured to operate using the ESP-NOW protocol, enabling it to receive structured data transmitted from the transmitter unit. The received data packet contains joystick position values and the push-button state, which are processed through a callback function upon successful reception. The callback function updates the corresponding global variables representing joystick movements and button status. Based on these inputs, the embedded program generates appropriate control signals for the motor driver and relay modules. The propulsion motors are controlled according to the joystick inputs, where the system remains in a stationary state when the joystick is in the neutral position and moves in different directions based on varying input combinations. The conveyor mechanism is controlled using the push-button input; when activated, the motor is driven using a Pulse Width Modulation (PWM) signal to regulate its operation. This ensures efficient control of both movement and waste collection mechanisms. The overall logic of the embedded programming for both transmitter and receiver ESP32 units is illustrated using a flowchart, as shown in the corresponding figures.

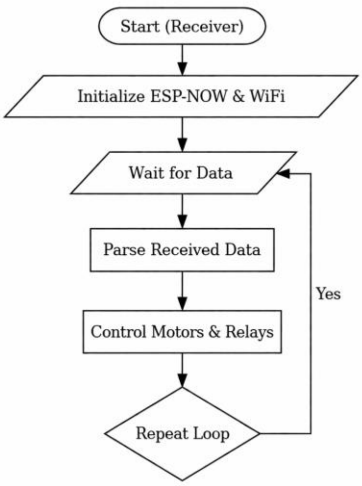

Fig -6: Flowchart of Receiver ESP32

7. RESULTS AND DISCUSSION

A fully functional prototype of the solar-powered aquatic trash collector was successfully developed and implemented, integrating key subsystems including the photovoltaic (PV) module, mechanical floating framework, propulsion unit, and conveyor-based waste collection mechanism. The prototype demonstrates effective coordination between electrical, mechanical, and control components, validating the feasibility of the proposed design for real-time aquatic waste removal.

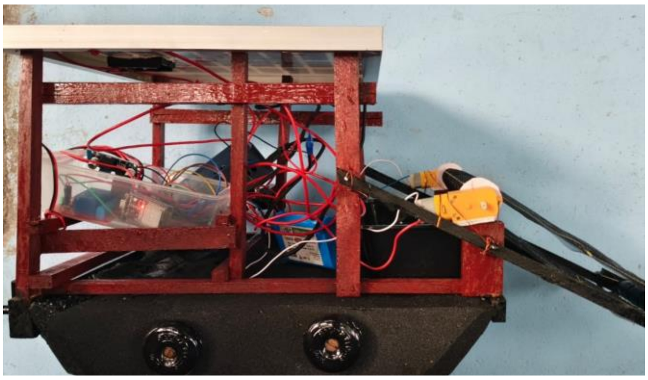

Fig -7: Mechanical structure

The mechanical frame of the proposed system is fabricated using rigid polyurethane foam, repurposed from an old refrigerator, due to its lightweight nature, buoyancy, and water-resistant properties, making it suitable for floating applications. To enhance structural strength and stability, small square unfinished wooden rods are used as a supporting framework, providing rigidity and proper alignment of components. The conveyor belt mechanism is constructed using a mosquito mesh net, which is lightweight, flexible, and capable of effectively capturing floating waste while allowing water to pass through.

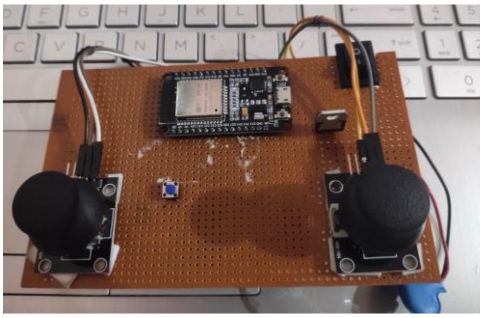

Fig -8: Navigation unit

A remote unit was developed to manage the navigation and operation of the prototype, consisting of joystick modules, a push-button switch, an ESP32 microcontroller, and a battery power supply. The joystick modules enable directional control of the propulsion system, while the push button is used to operate the conveyor mechanism. All components were assembled on a perforated PCB board to ensure compact arrangement, ease of handling, and reliable electrical connections.

7.1 Field Test

The developed prototype demonstrated optimum and comparatively robust performance within its design constraints, effectively collecting floating waste during field testing in a controlled aquatic environment. The system exhibited stable operation, reliable navigation, and efficient waste collection, validating the practicality and effectiveness of the proposed design.

Fig -9: Side View

Fig-10: Trash Collecting

Fig -11: Navigation Test

8. CONCLUSION

The solar-powered aquatic waste collection system developed in this work demonstrates an effective and sustainable solution for removing floating waste from water bodies. The integration of a photovoltaic (PV) energy system with embedded control using ESP32 microcontrollers and a conveyor-based waste collection mechanism ensures efficient and environmentally friendly operation. The prototype successfully achieved real-time navigation and waste collection through a wireless control system based on the ESP-NOW protocol, providing low-latency and reliable communication.

The experimental results confirm that the system performs efficiently under controlled conditions, exhibiting stable operation, good manoeuvrability, and effective waste collection capability. The use of lightweight and low-cost materials in the mechanical structure further enhances the practicality and affordability of the system. Although certain limitations exist, such as dependence on solar irradiance and reduced efficiency for heavier waste, the overall design proves to be a viable approach for small and medium-scale aquatic cleaning applications.

In conclusion, the proposed system offers a cost-effective and environmentally friendly solution for aquatic waste management. With further improvements such as automation, sensor integration, and enhanced power management, the system can be scaled and adapted for real-world deployment in various water bodies, contributing to cleaner and healthier aquatic environments.

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