

DESIGN AND DEVELOPMENT OF A POND SURFACE CLEANING ROBOT WITH SOLAR POWER INTEGRATION

Saitejasri Saini^{1,*}, Alekya Kummari², Sahithi Valdas³, N. Bhoopal⁴

Abstract

There has been a significant increase in water pollution with waste products such as plastic waste, leaves, algae, paper waste, and organic waste as a result of the rapid pace of urbanization and wrong waste disposal practices. This results in poor water quality and environmental hazards among others. Conventional systems for cleaning ponds use man-power and fuel-operated machines that are not only labor intensive and time consuming but are not suitable for continuous operation in larger and isolated bodies of water. This paper discusses the development of a solar-powered robotic pond cleaning device with wireless monitoring capability and manual control features.

The proposed design involves the use of a light foam structure for the boat with integration of the 12V/18W solar panel, 12V/6AH rechargeable battery, two DC motors for driving, and a conveyer belt system to collect the waste. The control of the robotic boat is done using the ESP32 microcontroller for both movement and waste collection operation. Communication for the purpose of controlling the device wirelessly is done via the HC-05 Bluetooth module and the mobile application on a mobile phone. Further, the proposed device features wireless remote monitoring capabilities using the ESP32-CAM module that provides real-time video streaming. As a consequence, the robotic boat operates independently and autonomously in the daytime without external power supply, using solar energy. The efficiency of waste collection from the surface was found to be 91%-93% at an optimal speed of 0.4-0. m/s. It is concluded that the presented design is a simple, cost effective, environmentally friendly, energy efficient solution for continuous cleaning of large water surfaces.

Keywords: Pond cleaning robot, Solar power, ESP32, IOT, Bluetooth, Waste collection, Embedded system, Water quality.

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INTRODUCTION

Freshwater bodies such as pond, small lakes, and reservoirs for irrigation are important for farming activities, aquaculture, drinking water supply, and biodiversity. However, the increasing trend in urbanization and the disposal of agricultural runoff has led to the accumulation of floating waste like—plastic debris, leaf litter, algae mats, and other organic waste —on the water surface. Floating pollutants cause a reduction in the level of dissolved oxygen levels, blocks sunlight needed for subaquatic photosynthesis, degrades water quality, and endangers aquatic life [1].

Manual removal of pollution from ponds involves the use of nets and boats to pick up trash. Manual cleaning requires workers to remove the trash from the ponds. This method is neither safe nor cost-efficient because workers have to deal with dirty

and contaminated water. It takes a lot of physical effort, and it is not very cost-effective. However, these devices are expensive, consume a lot of electricity, and are suitable only for large water bodies like lakes [2].

Advances in embedded systems, Internet- of- Things (IoT) connectivity, and solar energy harvesting now make it feasible to deploy small, autonomous, low-cost robotic platform for surface cleaning. Although there exist some prior works on water-surface robots [1]-[6]; however, most works involve the use of AC power or expensive sensors, limiting their adoption in rural or resource- constrained settings.

In this paper, we propose a pond surface cleaning robot that will solve these problems by employing the following innovations: (i) a 12V/18W photovoltaic panel for sustainable energy provision to the on-board systems; (ii) ESP32 microcontroller for wireless control; (iii) ESP32-CAM for real-time visual feedback; and (iv) Conveyor belt mechanism for effective waste collection. The system achieves a collection efficiency of 91-93% at an estimated total hardware cost of approximately INR 6K.

The remaining sections of this paper are organized as follows: Section II reviews related work. Section III describes the system architecture and hardware design. Section IV presents the software design and control algorithms. Section V reports experimental results, and section VI concludes the paper.

RELATED WORK

Premkumar *et al.* [1] developed a wireless autonomous Raspberry Pi and IoT are used to make a robot that cleans the surface of larger bodies of water. The system works well, but it needs a constant power supply, which makes it too expensive to use on a small scale.

Kong *et al.* [2] propose the development of an intelligent water- surface cleaning robot that implements dynamic grasping of waste based on YOLOv3- based object detection and sliding- mode control to dynamically grasp waste. But the computational cost of deep learning inference needs powerful hardware that can't run on solar power alone.

Tatar *et al.* [3] created a robot that cleans the surface of water in small ponds using solar power, but they said it couldn't handle a lot of waste and wasn't very good at avoiding clogs.

Manikandan *et al.* [4] expanded this idea by adding IoT monitoring, but they didn't include real-time video streaming and instead used GSM connectivity, which costs money every time it is used.

Anas *et al.* [5] included waste segregation based on image processing, but the system only works on AC power and is meant for bigger industrial tanks.

Thomas and Aswathi [6] introduce a solar-powered robot equipped with manual radio communication control and lacking remote IoT functionality and visual monitoring.

The main innovation of the proposed system lies in the combination of self- reliance of power source, efficient wireless communication protocol based on Bluetooth control, ESP32-CAM video feedback, and a small, low-cost than what has been reported in previous works (see Table 3).

SYSTEM ARCHITECTURE AND HARDWARE DESIGN

System Overview

The suggested robotic system (Figure 1) is a self-propelled, floating platform with the following five major systems incorporated: (1) power system, (2) Sensory & Monitoring System, (3) Control & Communication System, (4) Propulsion System, and (5) waste collection system. The interaction of these systems is shown in the systems is shown in the block diagram below.

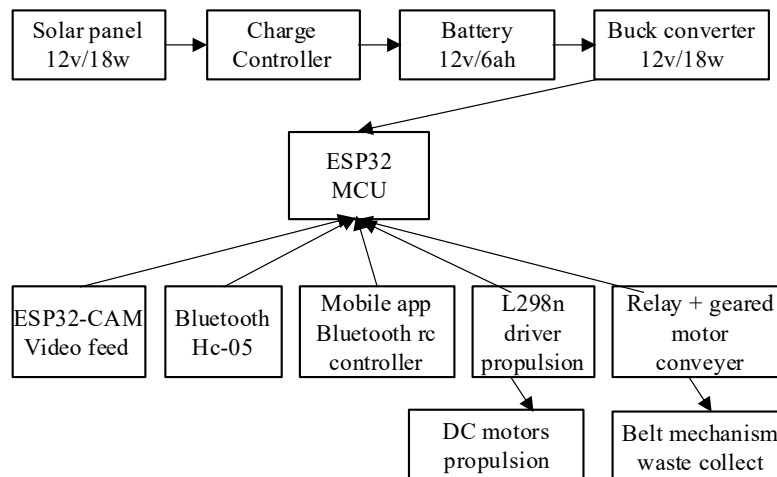


Figure 1. System Block Diagram of the solar- powered pond cleaning robot

Power Subsystem

There is a 12V/18W mono-crystalline solar panel on the upper deck of the foam platform. It is positioned horizontally to get the most sunlight. A charge controller (10A) connects the panel to a 12V/6000mAh Li-Ion battery pack that has protection against overcharging and deep discharging. A buck converter changes the 12V to V for the ESP32 and other ICs. The estimated total continuous load is about 9.15 W (Table 1), which gives the battery enough extra power to charge in full sunlight.

Control and Communication Subsystem

The ESP32 serves as the primary controller, handling communication, motor control, and system monitoring. And the HC-05 Bluetooth module lets you control things from a mobile app over short distances (less than 10m). The system uses FreeRTOS to handle a number of tasks well, such as processing commands, connecting to Bluetooth, controlling motors, and keeping an eye on safety [7].

Sensing and Monitoring Sub System

The ESP32-CAM module has OV2640 2MP sensor and sends MPPEG video over Wi- Fi at about 10 frames per second. This lets the operator see areas with a lot of trash and guide the robot accordingly. The system can be accessed through a web interface or web server that is hosted on the ESP32-CAM itself. You can see it in any browser or the companion mobile app.

Propulsion Subsystem

Two motors of 12V, 150 RPM DC type can be found on the left and right side of the floating platform powering the propellers. These motors are operated using L298N Motor controller that receives control signal from ESP32 in order to switch the direction of the motors. Using the system's differential drive allows for moving in forward, reverse, turning directions, which is helpful when operating on water surface.

Waste- Collection Subsystem

The mesh conveyor belt lifts floating waste off water surface and drops it inside collecting vessel attached to the device (capacity of the on-board bin is 0.5L). This action is performed with help of relay module controlling 12V, 60RPM geared motor. Using the sloped design helps with collecting of waste, whereas mesh provides for water drainage and prevents waste (plastic/leaves) loss [8].

SOFTWARE DESIGN AND CONTROL ALGORITHM

Firmware Architecture (ESP32)

The ESP32 firmware is written in FreeRTOS operating system with the use of Arduino IDE platform. The main control loop works at 50Hz and takes care of controlling the conveyor system, DC motor

control, Bluetooth command processing, computing, and safety. The ESP32 controls the motor in response to the commands received via the Bluetooth module. There is an incorporated watchdog circuit to ensure robot safety through motor shut off in the event of lack of command for a predetermined time interval [9].

Table 1. below contains all hardware components, their specifications and what they do in the system.

Components	Specifications	Role in system	Qty
Solar panel	12V, 18W	Renewable energy generation	1
Charge controller	12V PWM/MPPT	Battery over- charge protection	1
Li-Ion battery	12V, 6000mAh	Energy storage & supply	1
Buck converter	12 to 5V/3.3V	Regulated MCU Supply	2
Esp32 MCU	240MHz dual-core	Navigation, IoT & Bluetooth control	1
ESP32-CAM	OV2640,2MP	Real- time visual monitoring	1
L298N Motor driver	2A PER Channel	DC motor direction/speed control	1
DC Propulsion motor	12V, 150 RPM	Robot locomotion on water	2
DC Geared motor	12V,60RPM High torque	Conveyor belt actuation	2
Relay	50V,10A	Conveyor motor switching	1
HC-05 Bluetooth module	Class 2,10 m range	Manual Bluetooth control interface	1
Foam platform	500*400*50mm	Buoyancy and mechanical frame	1

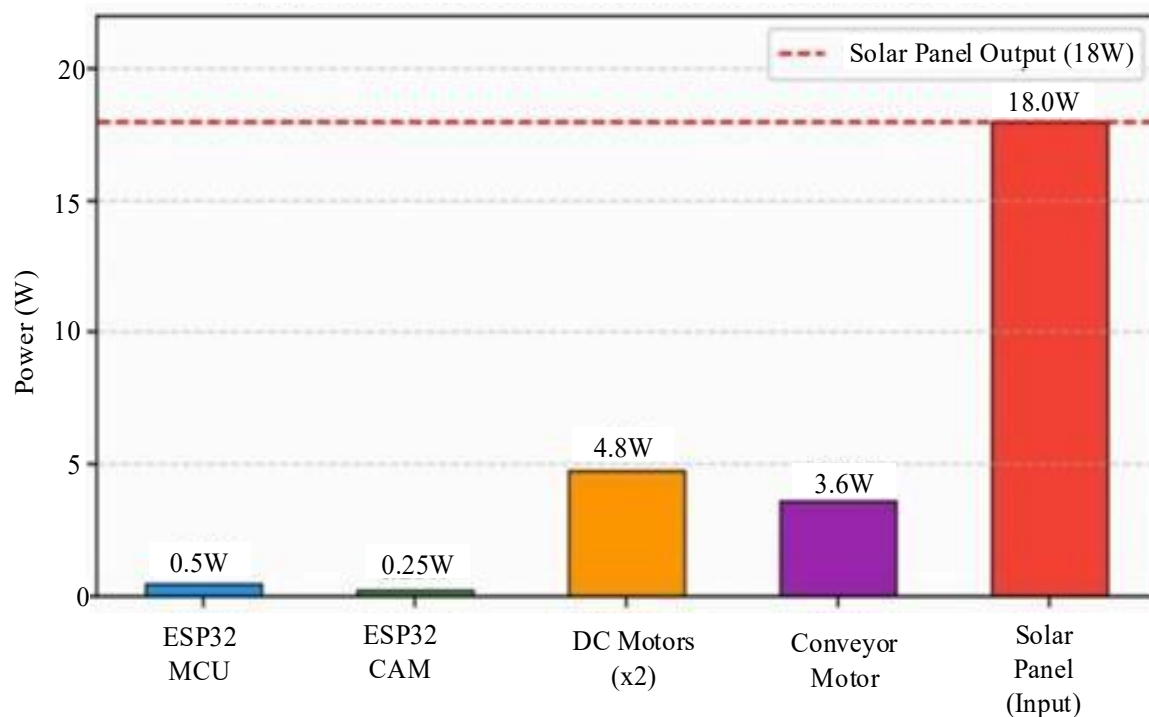


Figure 2. Component Power Consumption vs. Solar Panel output (18W)

Control Algorithm

The control algorithm operates as follows:

Step 1: Initial Setup of System Components – GPIO pins, PWM channels, Wi-Fi Access Point Bluetooth Serial Port, ESP32-CAM Streaming Server.

Step 2: Command Reception- Periodically check status of TCP Socket of Wi-Fi and UART buffers of Bluetooth. The single- byte tokens will be used for encoding commands, e.g., F – move forward, B – move backwards, L – move left, R – move right, S – stop movement, C – activate/deactivate conveyor.

Step 3: Motor Control – Convert command token to L298N duty cycle and direction control values. By default speed will be 70% of maximum PWM to ensure stable movement.

Step 4: Conveyor Actuation – “C” Command can be used to toggle relay for conveyor activation or deactivation at certain predefined times.

Step 5: Safety Watchdog – In case of no new valid command reception after > 2seconds robot will stop its movement to avoid drift.

Mobile Application

We use the Bluetooth RC Controller program to control the robot. It has a simple interface with directional commands like forward, backward, left, right and stop, as well as a control for the conveyor. The app lets you control the robot manually in real-time from a distance of about 10 meters. This is possible because the app talks to the ESP32 through the HC-05 Bluetooth module. The ESP32 uses the motor driver to control the motors after it gets and processes the commands. This lets the user easily control the garbage collection system and move the robot around. The technology is good for manual use in small bodies of water because it makes sure that control is quick and smooth [10].

EXPERIMENTAL RESULTS AND DISCUSSION

Test Setup

There were experiments done in a controlled outdoor pond (4 m*3 m, depth = 0.8 m) that had known amounts of floating plastic waste (polythene bags) and organic debris (dry leaves) in it. Three trails were performed for each condition, and the mean values are presented (Table 2).

Performance Results

The maximum efficiency of debris or waste collection by the robot is 91-93% when its speed is 0.4-0.5 m/s (Figure 3). For speed lower than 0.3 m/s, the conveyor tries to move the garbage away. When speed exceeds 0.6 m/s, waves appear that prevent frequent contact between the mesh and the water surface. The optimal speed selected for testing during daytime was 0.45 m/s. Figure 4 presents the graph of the battery charge state (SoC) during an 8- hour period.

Solar Powering and Battery Capability

Under direct sunshine conditions (about 1000W/m²). The solar power module delivers 1.3A at 12V (15.6W), marginally above the power Requirements of the motor and electronic components that is estimated to be 9.15W. This will keep the battery powered when in use. In case of zero solar power generation such as at night or during rainy periods, the fully charged battery capacity of 6000mAh will last up to 80 minutes under full load usage conditions (Figure 5).

Table 2. Experimental Performance Results

Test parameter	Condition	Results	Status
Robot speed	Open water, flat surface	0.4-0.5 m/s	Pass
Collection efficiency	Mixed plastic + leaves	91-93%	Pass
Solar charging rate	Full sunlight(1000W/m ²)	1.3A at 12V	Pass
Battery life	No solar, full load	≈80min	Pass
Bluetooth range	HC-05 Line of sight	≤10m	Pass
Video latency	ESP32-CAM, local network	<400ms	Pass
Waste bin capacity	Leaves + plastic debris	≈0.5L	Pass
Clog resistance	Dense algae patch (simulated)	No jam observed	Pass



Figure 3. Prototype Model of the Robot

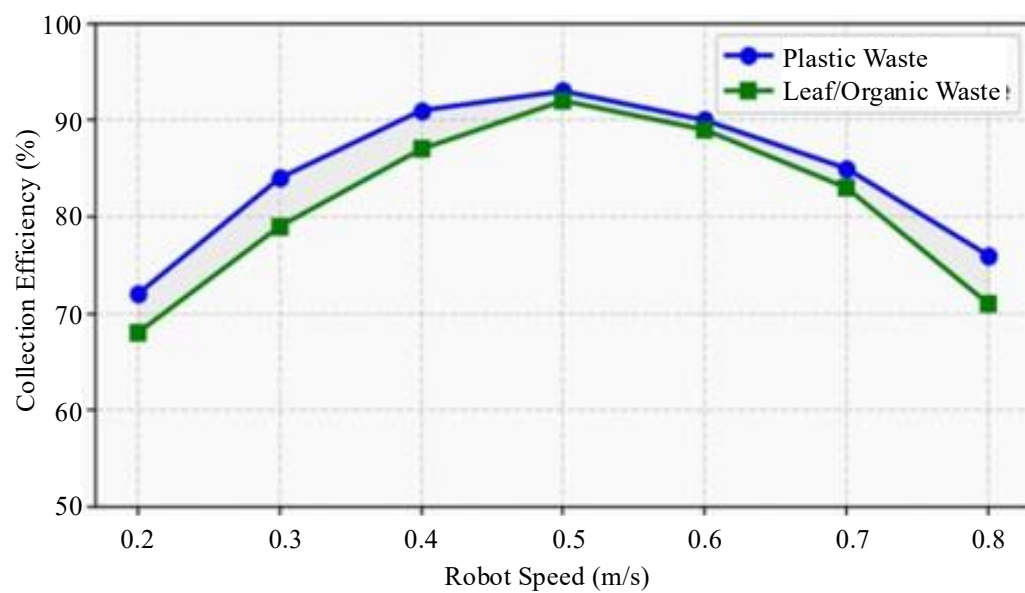


Figure 4. Waste Collection Efficiency vs. Operating Speed

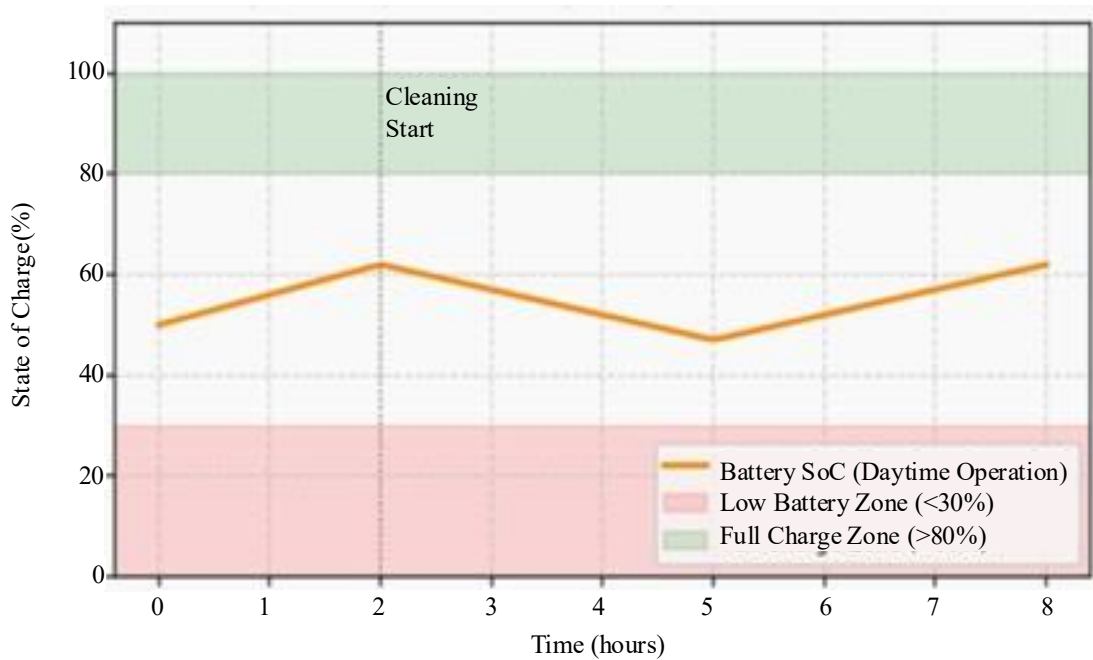


Figure 5. Battery State of Charge during Solar- Assisted Operation

Comparative Analysis

Table 4 benchmarks the proposed system against four representative prior works across key design parameters.

Table 3. Comparative analysis is shown below.

Feature	Proposed system	Prem kumar <i>et al.</i> [1]	Kong <i>et al.</i> [2]	Tatar <i>et al.</i> [3]
Control mode	IoT + Bluetooth	IoT (Wi-Fi)	Autonomous AI	Manual/Auto
Visual monitoring	Yes (ESP32-CAM)	No	Camera(CV)	No
Waste type	Plastic, leaves	General debris	Dynamic objects	Leaves, plastic
Scalability	Small ponds	Lakes	Large bodies	Small ponds
YOLOv3 detection	No	No	Yes	No

Table 4. Comparative analysis with existing systems

Feature	Proposed system	Prem kumar <i>et al.</i> [1]	Kong <i>et al.</i> [2]	Tatar <i>et al.</i> [3]
Power source	Solar+ battery	AC/DC Supply	Battery only	Solar + Battery
Cost Category	Low	Medium	High	Low – medium

The suggested system is the best option for small pond maintenance because it is cheap, solar-powered, can be controlled wirelessly, and can be monitored in real- time.

CONCLUSION

In this paper, the design, development, and experimental testing of a solar powered robot designed to clean the surface of the pond were discussed. The main features include: (1) a self- reliant power generation system that harnesses energy from the sun and runs on its own; (2) use of Bluetooth as means for control; (3) the use of ESP32-CAM for real-time monitoring; and (4) an efficient yet inexpensive conveyor belt system to collect waste. As per the experimental findings, the efficiency in collecting the waste material was up to 91-93% at 0.45 m/s optimal speed of the vehicle, the communication was reliable, and floating and overall operation was safe. The total cost of the hardware comes out to be 6000/-, which is a very low price point for municipalities, aquatic farm owners, and other organizations.

FUTURE WORK

Further improvements can be made by considering the following: (a) Incorporation of a GPS module for autonomous navigation, (b) Incorporation of water quality sensors (pH Value, turbidity, dissolved oxygen) for environment monitoring, (c) classification of waste based on images through machine learning and (d) Scaling of the system for large area ponds using multi-robot cooperation.

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