

Design and Development of a Solar-Assisted Water Surface Garbage Collection Boat with Two-Way Telemetry and GPS Return-to-Home

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Abstract

Floating litter such as plastic bottles, carry bags, thermocol and aquatic weeds gathers on lakes, ponds, temple tanks and slow-moving rivers. It is usually cleared by hand from a manned boat, which is slow and exposes workers to polluted water, while commercial skimmer vessels and aquatic drones cost far more than small water bodies can justify. This paper presents a low-cost, solar-assisted, radio-controlled boat that an operator drives from the bank to sweep floating waste into a bow-mounted bin. A handheld Arduino Nano remote and an ESP32-based boat share one two-way nRF24L01+ PA/LNA link at 2.4 GHz. The remote sends a 4-byte control packet 20 times per second, and the boat returns an 18-byte telemetry packet inside every acknowledgement, carrying hull roll and pitch (MPU6050 with a complementary filter), battery voltage, GPS position, speed and distance to home for display on an OLED. The boat steers by differential thrust of two DC motors through an L293D driver, so it needs no rudder. On a button press, or when the link is silent for more than 1 s, it returns to a stored home point using haversine distance, initial bearing and proportional heading correction. A deck-mounted 12 V panel charges the battery through a charge controller. Design calculations predict 3.4–4.3 h of full-throttle running from a 58 Wh pack, solar recovery of 50–60 % of the pack per sunny day with a 10 W panel, a working radio range of about 275–490 m over water, and a component cost of about Rs. 8,420.

.Keywords: water surface cleaning, floating waste collection, radio-controlled boat, nRF24L01+, ESP32, telemetry, GPS return-to-home, differential thrust, solar charging

I. INTRODUCTION

Lakes, ponds, temple tanks and slow-moving rivers supply drinking water, irrigation, fisheries and recreation to the towns that grow up around them, and they also collect a good deal of those towns' litter. Plastic bottles, carry bags, wrappers, thermocol pieces, flowers and offerings, leaves and aquatic weeds drift on the surface and pile up against the banks. The scale of the problem is well documented. Jambeck et al. [1] estimated that between 4.8 and 12.7 million tonnes of plastic entered the oceans from land in 2010 alone, and global river models [2], [3] show that a substantial share of it reaches the sea by river, with small urban rivers carrying a far larger share than their size would suggest. Closer to home, floating waste blocks sunlight, uses up dissolved oxygen as it decays, harms fish and birds, gives mosquitoes a breeding ground along the edges and spoils public spaces that people use every day.

In many places this waste is still removed by hand. Workers row out with nets and rakes, which is slow and tiring, carries a real risk of drowning and keeps them in direct contact with contaminated water. Trash-skimmer vessels and commercial aquatic drones do exist, but their price and size put them out of reach of the local bodies, housing societies, temple trusts and institutions that actually look after small water bodies.

This paper presents a small radio-controlled (RC) boat that an operator drives from the bank to sweep floating waste into a bin at the bow. The boat and a handheld remote talk over a single two-way nRF24L01+ 2.4 GHz link. The operator steers with a joystick, and the boat reports its tilt, battery voltage and GPS position back to an OLED screen on the remote. One button sends the boat back to a stored home point, and the same routine takes over

automatically if the radio link drops. A solar panel on the deck tops up the battery through a charge controller, so the boat can stay on the water longer between shore charges.

The main contributions of this work are:

- A low-cost cleaning boat built entirely from widely available modules (ESP32, Arduino Nano, nRF24L01+, MPU6050, NEO-6M GPS and L293D) and sized for ponds, lakes and temple tanks.
- A bidirectional radio scheme that uses the acknowledgement-payload feature of the nRF24L01+ to return 18 bytes of telemetry with every 4-byte command, without switching either radio between transmit and receive modes in software.
- Live telemetry on the handheld remote, covering tilt, battery voltage, GPS fix, distance to home, operating mode and link status, with warnings for excessive tilt and low battery.
- A GPS return-to-home routine based on haversine distance, initial bearing and proportional heading control, which doubles as a link-loss failsafe.
- On-board solar charging, a quantitative design analysis of power, radio range, link timing and cost, and a staged bench-to-water development method that similar projects can reuse.

The rest of the paper is organised as follows. Section II reviews related work and patents, and Section III states the problem and objectives. Section IV covers the development method, hardware, software and radio protocol, while Section V describes the system architecture, working principle, circuits and firmware. Section VI presents the design calculations, the validation plan and a discussion of the results, and Sections VII and VIII give the conclusions and future scope.

II. LITERATURE REVIEW

Water-surface cleaning machines reported in the literature fall broadly into three groups: (i) manually driven or radio-controlled boats that carry a passive net or bin, (ii) boats with an active collector such as a conveyor belt or rotating rake, and (iii) autonomous surface vehicles that use GPS waypoints, cameras or LiDAR to find and collect waste. Most student and low-cost designs combine a microcontroller, usually an Arduino or an ESP32, with DC motors and a battery, and many suggest solar charging as an improvement.

Prakash et al. [4] built a floating trash collector in which a motor-driven spiked conveyor lifts debris into a storage tank. They proposed solar power and a fill-level indicator as future additions, but their boat gives the operator no feedback. Fitriadhy et al. [5] designed an autonomous low-wave catamaran sea cleaner that detects obstacles with LiDAR and recognises debris with a camera and a neural network. It is capable, but it depends on costly sensors and on-board computing. Lim and Kok [6] developed an IoT lake-cleaning machine in which a Raspberry Pi runs OpenCV object detection and alerts operators when the tank is full or the battery level changes, which shows how useful it is to keep the person in charge informed of the machine's state.

Kann et al. [7] proposed a battery-powered river cleaner with an ESP32-CAM for live video, ultrasonic and PIR sensors and IoT monitoring. Because monitoring runs over Wi-Fi, it only works where there is network coverage near the water. Rajaraja et al. [8] described an ESP32-based aquatic robot that classifies floating objects with a YOLO model on edge hardware and reports through the Blynk IoT platform. Cheong [9] built an autonomous surface vessel that follows GPS waypoints; ROS Gazebo simulations showed good yaw and straight-line tracking with some oscillation on curved paths, which supports GPS-based heading control on small craft. At the commercial end, the WasteShark drone [10], roughly 190 cm × 140 cm × 45 cm with a capacity of about 550 L, proves that small electric collecting boats are practical, but it is priced for ports and municipalities rather than for village ponds.

Two enabling technologies are central to the present design. Abdelrahim et al. [11] evaluated an nRF24L01+-based sensor node in three urban propagation scenarios and found that the link held up reasonably well even in difficult conditions, which supports the use of the nRF24L01+ with a PA/LNA front end as a low-cost link, provided line of

sight is maintained. Mahony, Hamel and Pflimlin [12] established complementary filtering as an effective and inexpensive way to fuse gyroscope rates with accelerometer gravity measurements into drift-free attitude estimates. Table I summarises the reviewed work.

TABLE I. SUMMARY OF REVIEWED LITERATURE

Ref.	Approach	Key features	Gap with respect to this work
[4]	Floating trash collector	Spiked conveyor, storage tank	No telemetry, no return-to-home
[5]	Autonomous sea cleaner	Low-wave catamaran, LiDAR, camera with neural network	High cost, complex hardware
[6]	IoT lake cleaner	Raspberry Pi, OpenCV, status alerts	Needs a network; higher cost
[7]	River cleaner boat	ESP32-CAM, ultrasonic and PIR sensors, IoT	Limited by Wi-Fi range; no homing
[8]	ESP32 aquatic robot	YOLO edge AI, conveyor, Blynk IoT	Needs Wi-Fi and edge-AI hardware
[9]	Autonomous surface vessel	GPS waypoints, ROS simulation	Simulation focus; costly platform
[10]	Commercial aquatic drone	Large bin, battery powered	Price and size unsuitable for small ponds

A search of Google Patents using the keywords “floating refuse collecting boat”, “water surface cleaning unmanned boat” and “floating object collection” turned up three closely related patents, summarised in Table II.

TABLE II. PATENT SEARCH SUMMARY

Patent No.	Title / Assignee	Key claims	Difference from present work
US4128068A (1978) [13]	Floating-refuse-collecting boat / Mitsubishi Heavy Industries	Twin-hull boat with a collector between the hulls; water jets push refuse into the collector	Large manned vessel; no remote control or telemetry
CN107600337A (2018) [14]	A kind of unmanned boat / Shaanxi Ouka Electronic Technology	Unmanned boat with bow guide, stern propeller, detachable collector, camera and wireless module	Video based; no return-to-home or solar charging claimed
CN116902155B (2024) [15]	Intelligent collection pontoon for floating objects / Jiangsu Jiuzhi Environmental Technology	Perforated conveyor, squeeze rollers, oil–water separation and filtration	Complex mechanism focused on oil separation; not low cost

Two patterns stand out from this review. Low-cost designs generally give the operator no feedback and have no safe way of recovering the boat, while autonomous designs rely on expensive sensors or on network coverage at the site. None of the papers or patents reviewed combines a low-cost differential-thrust RC boat with a bidirectional telemetry link, GPS return-to-home with a link-loss failsafe, and on-board solar charging. That combination is the gap this work sets out to fill.

III. PROBLEM STATEMENT AND OBJECTIVES

The problem addressed here is to design and build a low-cost, remotely operated surface boat that collects floating waste from lakes and rivers, keeps the operator informed of its condition in real time, and can find its own way back to a fixed home point. In practice this breaks down into five problems:

- Manual cleaning of water surfaces is slow and exposes workers to polluted water and to the risk of drowning.
- Commercial cleaning vessels and aquatic drones are too expensive and too large for small water bodies.
- Simple RC boats tell the operator nothing about battery level, stability or position, so a boat can run flat, capsize or drift out of range without warning.
- A boat that loses its radio link far from the bank has to be recovered manually.
- Battery-only boats need frequent shore charging, which cuts into working time.

The objectives of the work are:

1. To build a twin-motor boat that steers by differential thrust, without a rudder.
2. To set up a two-way nRF24L01+ link that carries joystick commands to the boat and sensor data back to the remote.
3. To measure hull roll and pitch with an MPU6050 and warn of instability or capsizing.
4. To monitor battery voltage and warn the operator well before the battery runs low.
5. To track the boat's position by GPS and show it on the remote.
6. To implement a button-triggered return-to-home function that drives the boat to a predetermined GPS point.
7. To display all telemetry on an OLED screen on the remote.
8. To charge the boat's battery from an on-board solar panel through a solar charge controller.

IV. MATERIALS AND METHODOLOGY

A. Staged Development Methodology

The boat is built and tested in stages, and each stage is proven on the bench before the hull ever touches water. Working this way keeps faults isolated and easy to trace (Fig. 1). In stage 1 the two nRF24L01+ modules exchange control and telemetry packets, and range and packet loss are measured outdoors. Stage 2 adds the joystick, return button and OLED of the remote unit. In stage 3 the L293D and both motors are wired up, and the differential mixing, motor directions and failsafe stop are checked. Stage 4 brings up the MPU6050, the battery divider and the GPS receiver one at a time, with the battery reading calibrated against a multimeter. Stage 5 covers solar charging: panel voltage and charging current are measured in sunlight, and the overcharge and low-voltage cut-offs of the controller are confirmed. Stage 6 mounts the motors and panel on the hull, seals the electronics and fits the collection bin. Stage 7 tests return-to-home, first on land by carrying the boat and then over a short distance on calm water. The final field trial (stage 8) records range, waste collected per run, battery life with and without solar charging, and return-to-home accuracy.

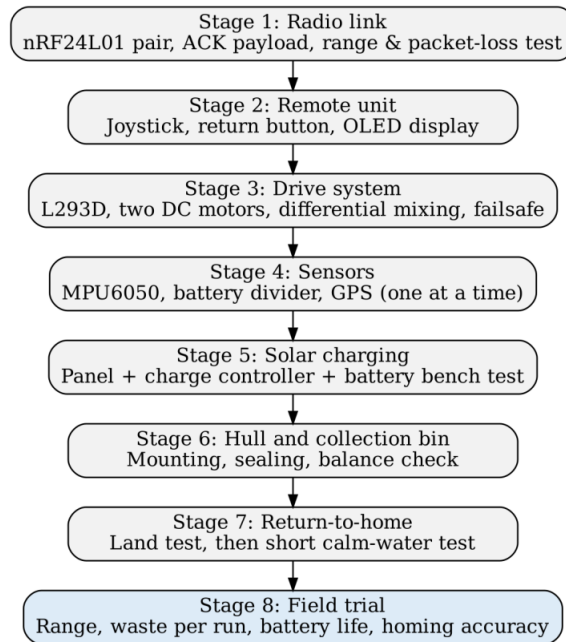


Fig. 1. Staged development methodology, from bench testing of the radio link to the field trial.

B. Hardware and Software

The boat unit is built around an ESP32 microcontroller [16] with an nRF24L01+ PA/LNA radio [17], an MPU6050 accelerometer–gyroscope [18], a u-blox NEO-6M GPS receiver [19], a battery-voltage divider and an L293D dual H-bridge driver [20] running two DC motors. Power comes from a battery pack that is charged by a deck-mounted solar panel through a solar charge controller. The remote unit uses an Arduino Nano, a two-axis joystick, a return-to-home push button, a second nRF24L01+ radio and a 0.96-inch SSD1306 OLED. Table III lists the hardware.

TABLE III. HARDWARE REQUIREMENTS

Sr.	Component	Specification	Qty.
1	ESP32 development board	Dual-core 240 MHz, Wi-Fi/Bluetooth, 3.3 V logic	1
2	Arduino Nano	ATmega328P, 16 MHz, 5 V logic	1
3	nRF24L01+ PA/LNA module	2.4 GHz, with SMA antenna and 5 V adapter	2
4	MPU6050 module (GY-521)	3-axis accelerometer and 3-axis gyroscope, I ² C	1
5	GPS module	u-blox NEO-6M with ceramic antenna	1
6	L293D motor driver	Dual H-bridge, 600 mA per channel, 4.5–36 V	1
7	DC motors with propellers	12 V, running current ≤ 0.6 A	2
8	Battery pack (boat)	3S Li-ion 11.1 V with BMS (or 12 V LiFePO ₄)	1
9	Solar panel	12 V, 10–20 W, monocrystalline	1
10	Solar charge controller	12 V PWM or MPPT, lithium charging profile	1
11	Buck converter	LM2596, 12 V to 5 V	1
12	OLED display	0.96 inch, 128 × 64, SSD1306, I ² C	1

Sr.	Component	Specification	Qty.
13	Joystick module	2-axis analogue with push switch	1
14	Push button and switch	Return-to-home button, power switch	1 each
15	Battery (remote)	2S Li-ion 7.4 V with holder	1
16	Hull and collection bin	PVC pipe or foam floats, mesh bin	1 set

The firmware is written in C/C++ in the Arduino IDE with the ESP32 board package. The RF24 library drives the nRF24L01+ with acknowledgement-payload support, TinyGPSPlus parses the NMEA sentences from the GPS module, the Wire library reads the MPU6050 over I²C, and the U8g2 (or Adafruit SSD1306) library drives the OLED. Schematics and PCB layouts are prepared in EasyEDA, KiCad or Fritzing.

C. Communication Protocol

Both directions of traffic share one nRF24L01+ pair. The remote sends a control packet every 50 ms (20 Hz), and the boat answers each one with a telemetry packet carried inside the acknowledgement. Because the radio hardware handles the acknowledgement, neither side has to switch between transmit and receive modes in software. The boat loads its next telemetry packet into the acknowledgement buffer as soon as a control packet arrives, so the data shown on the remote are never more than one control period old. Table IV lists the radio settings chosen for range, and Tables V and VI give the packet formats. PA/LNA modules are commonly advertised for up to about 1 km in open line of sight; over water, a few hundred metres is a more realistic working figure, as the link budget in Section VI-A shows.

TABLE IV. RADIO SETTINGS FOR RANGE

Parameter	Setting	Reason
Data rate	250 kbps	Lowest rate; best receiver sensitivity (−94 dBm [17])
PA level	Maximum	Longest range; PA/LNA modules with external antennas at both ends
RF channel	80 (2.480 GHz)	Inside the 2.400–2.4835 GHz licence-exempt band and above the commonly used Wi-Fi channels 1, 6 and 11
Auto-ACK retransmit	/ Enabled; 1500 μ s delay, up to 15 retries	Reliable delivery; the delay leaves time for an 18-byte acknowledgement at 250 kbps
Payload	Dynamic, ACK payload enabled	Telemetry rides on each acknowledgement

TABLE V. CONTROL PACKET (REMOTE TO BOAT)

Field	Size	Meaning
Throttle	1 byte	Joystick Y axis, forward and reverse
Turn	1 byte	Joystick X axis, left and right
Flags	1 byte	Return-to-home button, set-home command
Counter	1 byte	Packet number, used to detect lost packets

TABLE VI. TELEMETRY PACKET (BOAT TO REMOTE)

Field	Size	Meaning
Roll, pitch	2×2 bytes	Hull tilt from the MPU6050, in units of 0.01°
Battery voltage	2 bytes	In millivolts
Latitude, longitude	2×4 bytes	GPS position
Speed	1 byte	GPS ground speed
Distance to home	2 bytes	In metres
Status	1 byte	GPS fix, mode (manual or return-to-home), low-battery flag
Total	18 bytes	Within the 32-byte nRF24L01+ payload limit

Link-loss failsafe. If the boat receives no valid control packet for about 1 s, it stops both motors. If it has a GPS fix and a stored home point, it switches to return-to-home instead, so a boat that drifts out of range makes its own way back.

V. DESIGN OF THE PROPOSED SYSTEM

A. System Architecture

The system consists of two units joined by one two-way radio link: a handheld remote on the bank and the boat on the water (Fig. 2). The remote reads the joystick and the return-to-home button and sends them to the boat. The boat drives its two motors accordingly, reads its sensors and sends the readings back for display. The orange arrows in the lower part of Fig. 2 trace the power path from the solar panel through the charge controller to the battery, which supplies both the motors and the electronics.

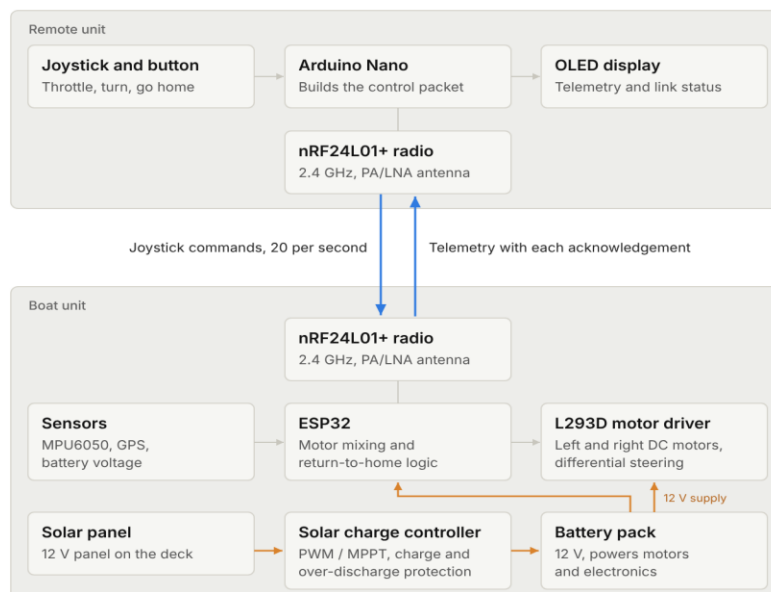


Fig. 2. Block diagram of the remote unit and the boat unit. Blue arrows show the radio link and orange arrows the power path.

B. Working Principle

1) Manual driving. The boat has no rudder. It steers by running its left and right motors at different speeds, and the joystick values are mixed into motor commands as

$$L = T + S, \quad R = T - S \quad (1)$$

where T is the throttle command (joystick Y axis) and S the turn command (X axis), both decoded to the range ± 255 , and L and R are the left and right motor commands, each constrained to ± 255 . The magnitude of each command sets the PWM duty cycle on one L293D enable pin, and its sign sets the direction inputs. Pushing the stick straight forward runs both motors equally and the boat goes straight. Pushing it sideways slows or reverses one motor so that the boat turns, and with the stick held fully sideways it spins on the spot.

2) Waste collection. As the boat moves forward, floating waste is guided into a mesh collection bin at the bow. The operator keeps an eye on the bin and brings the boat back to the bank to empty it when it is full.

3) Stability monitoring. Gyroscope angles drift over time and accelerometer angles are noisy whenever the hull moves, so the two are fused with a first-order complementary filter based on [12]:

$$\theta_k = \alpha(\theta_{k-1} + \omega \Delta t) + (1 - \alpha) \theta_{acc} \quad (2)$$

Here θ stands for either roll or pitch, ω is the matching gyroscope rate, Δt is the loop period and θ_{acc} is the angle obtained from gravity:

$$\theta_{r,acc} = \text{atan2}(a_y, a_z), \quad \theta_{p,acc} = \text{atan2}(-a_x, \sqrt{a_y^2 + a_z^2}) \quad (3)$$

where a_x , a_y and a_z are the accelerometer readings. With $\alpha = 0.98$ and $\Delta t \approx 20$ ms, the filter time constant is

$$\tau = \frac{\alpha \Delta t}{1 - \alpha} \approx 0.98 \text{ s} \quad (4)$$

so the gyroscope dominates over short intervals while the accelerometer slowly removes any drift. If the tilt exceeds a set limit (for example 20°), a warning appears on the remote, because an unevenly loaded bin or a passing wave can tip a small hull.

4) Battery monitoring. A resistor divider scales the battery voltage into the range of the microcontroller's ADC. The remote displays the voltage and raises a low-battery flag early enough for the boat to get back to the bank.

5) Solar charging. The deck-mounted panel feeds a solar charge controller that limits the charging voltage to suit the battery chemistry, disconnects the load before the battery is over-discharged and blocks reverse current at night. The panel is not meant to run the boat on its own. It tops up the battery during operation and recharges it while the boat is parked in the sun.

6) Return-to-home. The home point is either fixed in firmware or stored at launch from the first valid GPS fix. When the return button is pressed, the boat reads its current position (φ_1, λ_1) and computes the distance d and the initial bearing β to home (φ_2, λ_2) with the haversine formula [21]:

$$a = \sin^2\left(\frac{\Delta\varphi}{2}\right) + \cos\varphi_1 \cos\varphi_2 \sin^2\left(\frac{\Delta\lambda}{2}\right) \quad (5)$$

$$d = 2R_E \text{atan2}(\sqrt{a}, \sqrt{1-a}) \quad (6)$$

$$\beta = \text{atan2}(\sin\Delta\lambda \cos\varphi_2, \cos\varphi_1 \sin\varphi_2 - \sin\varphi_1 \cos\varphi_2 \cos\Delta\lambda) \quad (7)$$

where $\Delta\varphi = \varphi_2 - \varphi_1$, $\Delta\lambda = \lambda_2 - \lambda_1$ and $R_E = 6\,371\,000$ m is the mean radius of the Earth. The boat then compares β with its GPS course over ground ψ . The heading error is wrapped to the range $\pm 180^\circ$ by

$$e = [(\beta - \psi + 540^\circ) \bmod 360^\circ] - 180^\circ \quad (8)$$

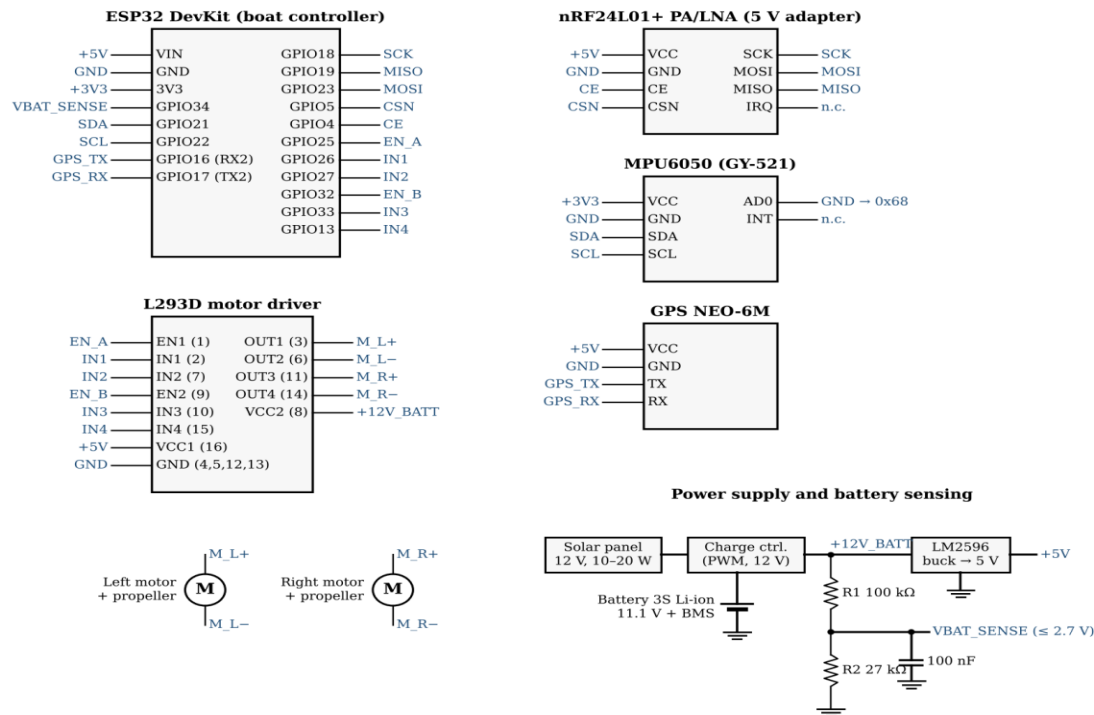
and converted into a turn command by a proportional law,

$$S = \text{sat}_{150}(K_p e) \quad (9)$$

where K_p is the steering gain and sat_{150} limits the command to ± 150 . Capping the turn command keeps the correction gentle and keeps the boat moving forward while it turns, which matters because course over ground is only meaningful while the boat is under way. The boat stops once d drops below 3 m. This radius is set just above the 2.5 m CEP horizontal accuracy of the NEO-6M [19], so that the boat does not circle the home point chasing GPS noise. Moving the joystick at any time during the return cancels it and hands control back to the operator.

C. Circuit Design

Fig. 3 shows the circuit of the boat unit. The nRF24L01+ sits on the VSPI bus of the ESP32 (GPIO18 SCK, GPIO19 MISO, GPIO23 MOSI) with GPIO5 as CSN and GPIO4 as CE. The MPU6050 uses I²C on GPIO21/GPIO22 (address 0x68, with AD0 grounded), and the GPS module is connected to UART2 (GPIO16 RX, GPIO17 TX). The L293D enable pins receive PWM from GPIO25 and GPIO32, and its direction inputs are driven by GPIO26, GPIO27, GPIO33 and GPIO13. The battery divider (100 k Ω / 27 k Ω , with a 100 nF filter capacitor) feeds GPIO34, an input-only pin on ADC1, which, unlike ADC2, remains usable even if the Wi-Fi of the ESP32 is enabled later. An LM2596 buck converter produces 5 V for the ESP32, the radio adapter, the GPS receiver and the L293D logic supply, while the L293D motor supply (VCC2) is taken directly from the battery. Both radio modules sit on 5 V adapter boards with on-board 3.3 V regulators, and a 100 μ F electrolytic capacitor is placed across each radio's supply pins because the PA/LNA version draws current in sharp bursts when it transmits.



Notes: nets with the same name are connected. 100 μ F electrolytic across nRF24 VCC-GND at the module. All grounds common. L293D VCC2 = motor supply (+12V_BATT); VCC1 = 5 V logic. GPIO34 is input-only (ADC1).

Fig. 3. Circuit diagram of the boat unit.

Fig. 4 shows the remote unit. Its nRF24L01+ uses the hardware SPI pins of the Arduino Nano (D13, D12, D11) with D10 as CSN and D9 as CE. The joystick axes are read on A0 and A1, the joystick switch on D2 and the return-

to-home button on D3, both with internal pull-ups enabled. The OLED (I²C address 0x3C) sits on A4 and A5. A 2S Li-ion battery feeds VIN through a power switch, and a 10 k Ω / 10 k Ω divider on A2 lets the remote measure its own battery voltage.

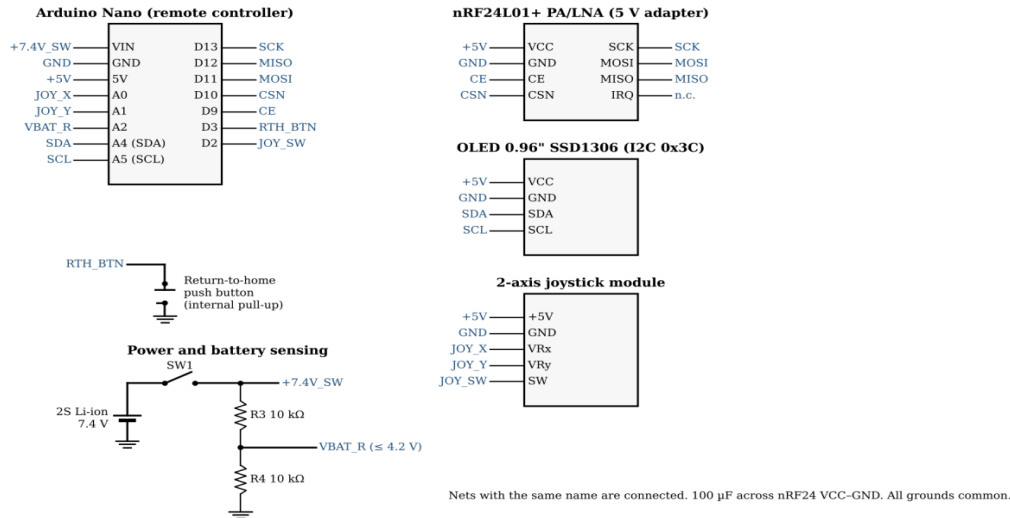


Fig. 4. Circuit diagram of the remote unit.

D. Firmware

The boat firmware runs a non-blocking loop (Fig. 5). On each pass it services the radio, applies the failsafe, computes motor commands in manual or return-to-home mode, reads the sensors and loads the next telemetry packet into the acknowledgement buffer. The remote firmware (Fig. 6) reads the joystick and buttons, transmits a control packet every 50 ms, decodes the telemetry that comes back and refreshes the OLED with battery voltage, roll and pitch, GPS fix status, distance to home, mode and link status. If no acknowledgement arrives for more than 1 s, the display shows LINK LOST.

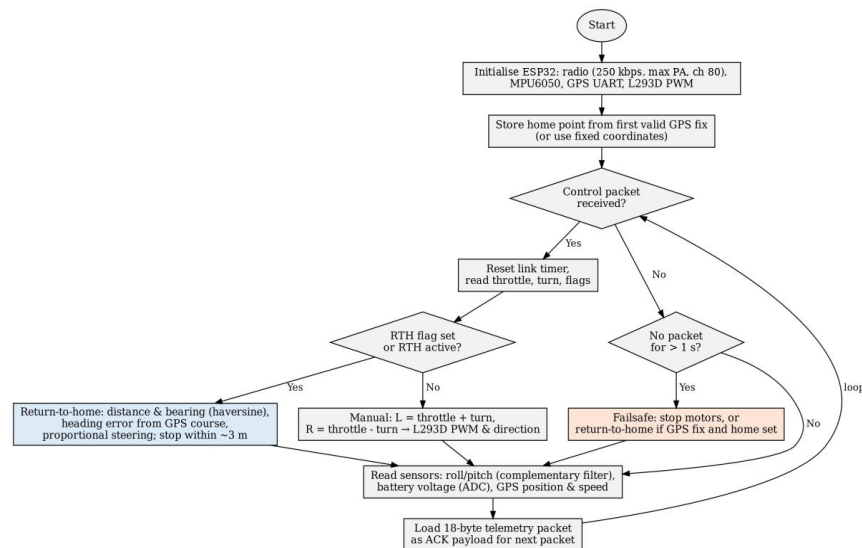


Fig. 5. Flow chart of the boat firmware.

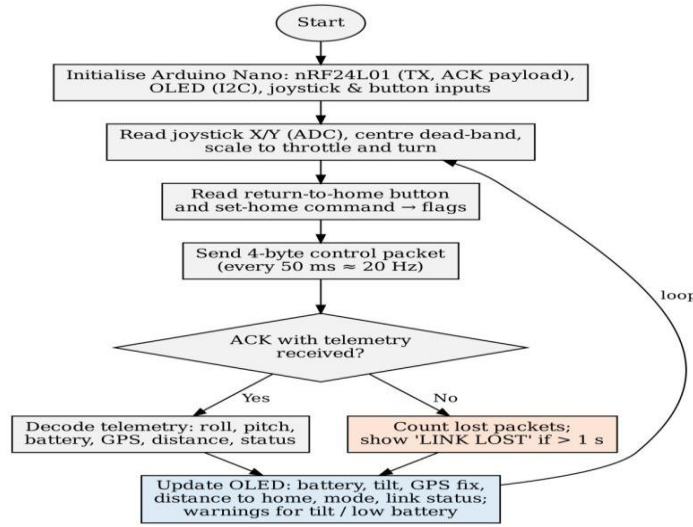


Fig. 6. Flow chart of the remote firmware.

VI. RESULTS AND DISCUSSION

The results in this section come from design calculations based on component data sheets and standard engineering models. They set the targets against which the prototype is tested in the validation plan of Section VI-B.

A. Design Calculations

1) *Battery voltage divider.* On the boat, the voltage at the ADC pin is

$$V_{\text{pin}} = V_b \frac{R_2}{R_1 + R_2} \quad (10)$$

With $R_1 = 100 \text{ k}\Omega$ and $R_2 = 27 \text{ k}\Omega$ the ratio is $27/127 = 0.213$, so a fully charged 3S pack at 12.6 V gives 2.68 V at GPIO34, and the firmware multiplies the calibrated pin voltage by $127/27 = 4.70$ to recover the battery voltage. The divider draws only about 0.1 mA, roughly 1.4 % of the pack's capacity per month if it is left connected. One detail deserves attention. At 11 dB attenuation the ESP32 ADC is most linear between about 0.15 V and 2.45 V [22], so the full-charge reading sits slightly above the linear region, where readings compress a little. The reading that matters most, the low-battery threshold, is unaffected: at 9.9 V (3.3 V per cell) the pin sees 2.10 V, comfortably inside the linear range, and calibration against a multimeter removes the remaining error. If accurate readings near full charge are wanted, reducing R_2 to 22 k Ω brings the full-charge pin voltage down to 2.27 V. On the remote, $R_3 = R_4 = 10 \text{ k}\Omega$ halve the 8.4 V of a full 2S pack to 4.2 V at A2, inside the 5 V range of the Arduino Nano ADC.

2) *Packet size and link timing.* The telemetry packet holds roll and pitch (4 bytes), battery voltage (2), latitude and longitude (8), speed (1), distance to home (2) and status (1), a total of 18 bytes that fits in a single 32-byte nRF24L01+ payload. The on-air time of an Enhanced ShockBurst packet is [17]

$$t_{\text{air}} = \frac{8(1+A+P+C)+9}{R_b} \quad (11)$$

where $A = 5$ is the address length in bytes, P the payload length, $C = 2$ the CRC length, the extra 9 bits form the packet control field and $R_b = 250 \text{ kbps}$ is the data rate. A 4-byte control packet therefore takes 0.42 ms on air and an acknowledgement carrying 18 bytes of telemetry takes 0.87 ms. Adding the 130 μs settling time before each transmission, one complete exchange takes about 1.55 ms, or roughly 3 % of the 50 ms control period. The 1500 μs retransmit delay in Table IV leaves enough time for the long acknowledgement to arrive, and even in the worst case of 15 retries an exchange finishes within about 33 ms, so retries never spill over into the next control period.

3) **Radio range.** The largest path loss the link can tolerate follows from the link budget

$$PL_{\max} = P_t + G_t + G_r - S_r \quad (12)$$

Taking a transmit power of about +20 dBm, which is typical of PA/LNA modules, 2 dBi antennas at both ends and the -94 dBm receiver sensitivity of the nRF24L01+ at 250 kbps [17], the budget gives $PL_{\max} \approx 118$ dB. In free space the path loss is

$$PL_{fs} = 20 \log_{10} \left(\frac{4\pi d}{\lambda_0} \right) \quad (13)$$

with $\lambda_0 = c/f \approx 0.121$ m at 2.48 GHz, which would allow a theoretical range of more than 7 km. Over water that figure means little. With the remote held about 1 m above the water and the boat's antenna about 0.3 m up, the radius of the first Fresnel zone,

$$r_1 = \sqrt{\frac{\lambda_0 d_1 d_2}{d}} \quad (14)$$

is already about 3 m at the midpoint of a 300 m path, ten times the height of the boat's antenna, so the water surface always cuts well into it. The direct ray then interferes with a strong reflection from the water, and beyond the crossover distance d_c the two-ray ground-reflection model applies [23]:

$$PL_{2r} = 40 \log_{10} d - 20 \log_{10}(h_t h_r), \quad d > d_c = \frac{4\pi h_t h_r}{\lambda_0} \quad (15)$$

For these antenna heights d_c is only about 31 m. Solving (15) with $PL_{2r} = 118$ dB gives a range of about 490 m with no margin and about 275 m with a 10 dB fade margin; Table VII summarises the budget. The result agrees with the working figure of a few hundred metres, and it also shows where the range comes from. Because the loss in this region depends on the product $h_t h_r$, doubling the height of the remote's antenna, for example by standing on a jetty or a ghat, extends the range by about 40 %, as much as an extra 6 dB of transmit power would. The estimate ignores the sensitivity gained from the LNA, which makes it conservative, while antenna mismatch, shadowing by the hull and Wi-Fi interference pull in the other direction.

TABLE VII. RADIO LINK BUDGET

Parameter	Value	Basis
Transmit power, P_t	+20 dBm	Typical nRF24L01+ PA/LNA module
Antenna gains, G_t, G_r	2 dBi each	SMA dipole antennas
Receiver sensitivity, S_r	-94 dBm	nRF24L01+ at 250 kbps [17]
Maximum path loss, $PL_{\max}$	118 dB	Eq. (12)
Antenna heights, h_t, h_r	1.0 m, 0.3 m	Hand-held remote; antenna on deck
Free-space range	≈ 7.6 km	Eq. (13); not achievable over water
Two-ray crossover distance, d_c	≈ 31 m	Eq. (15)
Two-ray range, 0 dB margin	≈ 490 m	Eq. (15)
Two-ray range, 10 dB fade margin	≈ 275 m	Recommended working range

4) **Energy budget.** The run time on battery alone and the energy recovered from the panel each day are

$$t_{\text{run}} = \frac{\eta_d V_b C_b}{P_{\text{load}}} \quad (16)$$

$$E_{\text{pv}} = P_{\text{pv}} H \eta_c \quad (17)$$

A 3S Li-ion pack of 11.1 V and 5.2 Ah stores $V_b C_b \approx 58$ Wh. Assuming each motor draws 0.5 A from the 12 V bus (about 12 W for the pair) and the electronics take another 1.5 W, the full-throttle load is $P_{\text{load}} \approx 13.5$ W. Using the whole capacity ($\eta_d = 1$) gives 4.3 h of continuous running, while keeping 20 % in reserve to protect the cells ($\eta_d = 0.8$) gives a more realistic 3.4 h. A 10 W panel receiving $H = 4\text{--}5$ peak-sun-hours a day at an overall PWM charging efficiency of $\eta_c \approx 0.7$ yields 28–35 Wh a day, enough to put back 50–60 % of a full pack while the boat is parked in the sun. A 20 W panel, the upper end of the range in Table III, roughly doubles this to 56–70 Wh, close to a full recharge every day. Table VIII summarises the budget. These are estimates, and actual figures will depend on motor load, water conditions and weather.

TABLE VIII. ENERGY BUDGET

Item	Basis	Result
Battery energy	11.1 V $\times$ 5.2 Ah	≈ 58 Wh
Motor load (two motors)	2 $\times$ 0.5 A $\times$ 12 V	12 W
Electronics	ESP32, radio, GPS, IMU, converter losses	1.5 W
Total full-throttle load	Sum of the above	13.5 W
Run time, full capacity	58 Wh $\div$ 13.5 W	≈ 4.3 h
Run time, 80 % usable capacity	0.8 $\times$ 58 Wh $\div$ 13.5 W	≈ 3.4 h
Solar energy, 10 W panel	10 W $\times$ 4–5 h $\times$ 0.7	28–35 Wh/day (50–60 % of pack)
Solar energy, 20 W panel	20 W $\times$ 4–5 h $\times$ 0.7	56–70 Wh/day (about one full charge)

5) Cost. At approximate 2026 market rates, the complete boat and remote cost about Rs. 8,420. The largest items are the battery pack (Rs. 1,500), the hull and collection bin (Rs. 1,200) and the two radio modules (Rs. 900). That is a small fraction of the price of a commercial aquatic drone [10], and every part is a standard module that can be bought and replaced easily.

B. Validation Plan

Table IX lists the bench and field tests the prototype has to pass, each with its method and acceptance criterion. The tests follow the staged sequence of Fig. 1, so each subsystem is signed off before the next one is added, and the analytical figures above supply the targets for range, timing and endurance.

TABLE IX. VALIDATION TESTS AND ACCEPTANCE CRITERIA

Sr.	Test	Method	Acceptance criterion
1	Radio range over water (line of sight)	Drive the boat away along a clear line of sight while the remote logs lost packets from the packet counter	A few hundred metres (≈ 275 m with margin) at < 5 % packet loss
2	Control packet rate	Count packets received at the boat over 60 s	≈ 20 packets per second
3	Failsafe on link loss	Switch the remote off while the boat is running	Motors stop, or return-to-home starts, within ≈ 1 s
4	Battery voltage reading	Compare the displayed voltage with a multimeter at several charge levels	Error within ± 0.1 V

Sr.	Test	Method	Acceptance criterion
5	Roll and pitch on a level surface	Place the boat on a level bench and log both angles	$0^\circ \pm 1^\circ$
6	Tilt warning	Tilt the hull by hand beyond the set limit	Warning shown above the limit (e.g. 20°)
7	GPS fix (cold start, open sky)	Power up outdoors and time the first fix	Fix obtained and shown on the OLED
8	Return-to-home stopping distance	Trigger return-to-home from several points and measure the final distance to home	Within a few metres of home (3 m threshold)
9	Solar charging	Measure charging current in sunlight	Charging indicated by the controller
10	Run time with and without solar	Run at constant throttle until the low-battery cut-off	≈ 3.4 h without solar; longer with solar
11	Waste collected per run	Weigh the bin contents after a timed run	Bin filled with floating waste

C. Discussion

The design addresses each of the eight objectives with low-cost, widely available modules. The acknowledgement-payload feature of the nRF24L01+ is the key to a simple two-way link: every control packet that reaches the boat brings back fresh telemetry, and a missing acknowledgement tells the remote at once that the link is weakening. Running the radio at 250 kbps gives up data rate, which this application does not need, in exchange for 9–12 dB more receiver sensitivity than the 1 and 2 Mbps modes [17], and the timing analysis shows that even at this slowest rate the channel is idle about 97 % of the time. Unlike the Wi-Fi and IoT designs in [7] and [8], the boat needs no network coverage at the water body, which matters at rural ponds and temple tanks.

Differential thrust removes the need for a rudder and servo, keeps the mechanics simple and lets the boat turn on the spot, which is handy when nosing into waste trapped near the bank. The complementary filter gives stable tilt angles at almost no computational cost, which is all a capsized warning needs. Return-to-home has one subtle weakness: without a compass, heading comes from the GPS course over ground, which is valid only while the boat is moving. The routine therefore starts by driving forward briefly before it corrects the heading. The NEO-6M updates at 1 Hz by default, and configuring it for its maximum rate of 5 Hz [19] gives the heading loop fresher data and smoother corrections.

The link-loss failsafe adds an important layer of safety, since a boat that drifts out of range tries to come home on its own instead of being lost. Solar charging does not replace shore charging, but by recovering half or more of the pack on a sunny day it noticeably extends working time for a boat that spends long periods parked on the water.

D. Limitations

- The L293D supplies only about 600 mA per channel, which limits motor size and therefore the size and speed of the boat. Its bipolar output stage also drops roughly 2–3 V at rated current [20], so the motors never see the full battery voltage and more than 1 W per motor is lost as heat.
- The nRF24L01+ needs a clear line of sight; trees, embankments and Wi-Fi interference all reduce the range.
- Without a compass, heading comes from GPS and is valid only while the boat is moving.
- GPS accuracy is a few metres, so the boat returns to the home area rather than to an exact spot.
- The prototype is meant for calm water; strong currents and waves are beyond its motor power.

- Solar output falls in cloudy weather and is zero at night, so a small panel extends run time rather than replacing shore charging.
- The panel adds weight and wind area high on the hull, which affects stability and has to be balanced against the load in the collection bin.
- The performance figures reported here are design estimates and remain to be confirmed by the field trials listed in Table IX.

VII. CONCLUSION

This paper has presented a solar-assisted, radio-controlled boat for collecting floating waste from lakes, ponds and slow-moving rivers. A handheld Arduino Nano remote and an ESP32-based boat communicate over a single two-way nRF24L01+ PA/LNA link. The boat steers by differential thrust, sweeps waste into a bow-mounted bin, and returns roll, pitch, battery voltage, GPS position, speed and distance to home in every radio acknowledgement for live display on an OLED. A haversine-based return-to-home routine with proportional heading control brings the boat back on command or when the link is lost, and a deck-mounted solar panel keeps the battery topped up.

The design analysis shows that a 4-byte command and an 18-byte telemetry reply occupy only about 3 % of the channel at 20 Hz, that a working range of roughly 275–490 m can be expected over water, and that a 58 Wh pack supports 3.4–4.3 h of full-throttle running, with a 10 W panel recovering 50–60 % of the pack on a sunny day. All of this comes for about Rs. 8,420 in widely available parts. The boat suits ponds, lakes, temple tanks, slow river stretches, swimming pools, fish ponds and water-treatment tanks, and it supports the United Nations Sustainable Development Goals [24], in particular SDG 6 (clean water and sanitation), SDG 7 (affordable and clean energy), SDG 11 (sustainable cities and communities) and SDG 14 (life below water).

VIII. FUTURE SCOPE

- Field trials on a local lake to measure range, endurance, waste collected per run and homing accuracy against the criteria in Table IX.
- A magnetometer (for example, a QMC5883L) to give heading at rest and improve return-to-home accuracy.
- A MOSFET-based motor driver such as the TB6612FNG or BTS7960 to cut driver losses and allow larger motors, hulls and bins.
- A conveyor-belt collector for active waste pick-up.
- Solar telemetry, showing panel voltage and charging current on the remote.
- Camera-based waste detection and fully autonomous area coverage.
- Water-quality monitoring with pH, turbidity and temperature sensors.

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