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Hydro Guard: An IoT-Based Intelligent River Cleaning Robot with Real-Time Water Quality Monitoring

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Abstract: Water pollution remains a critical environmental challenge, particularly in river ecosystems. Traditional manual approaches to river monitoring and cleaning are time-consuming, resource-intensive, and fail to provide real-time insights. This paper presents Hydro Guard, an IoT-based intelligent river cleaning robot that integrates real-time water quality monitoring, live video surveillance, automated surface cleaning, and remote navigation into a unified smart platform. The system employs an ESP32 microcontroller and ESP32-CAM module interfaced with pH, temperature, turbidity, and GPS sensors for comprehensive environmental monitoring. A motor-driven navigation mechanism enables controlled surface mobility, while an integrated dust collector continuously removes floating waste. Wireless communication facilitates real-time data transmission and remote control through a PC-based interface. Field validation in river environments of Tamil Nadu, India demonstrated that the system achieves sensor accuracy within 95% of laboratory standards, with less than 1% navigation error rate. The live surveillance system achieved low-latency video streaming with 94% visibility under standard daylight conditions. The proposed system offers a cost-effective, scalable, and autonomous solution for simultaneous water quality monitoring and surface cleaning, with significant implications for sustainable water resource management.

Index Terms: River Cleaning Robot, IoT, Water Quality Monitoring, ESP32, Real-Time Monitoring, Autonomous Navigation, Environmental Management, Wireless Communication, Turbidity Sensor, pH Sensor.

I. INTRODUCTION

Water pollution poses a severe and growing threat to aquatic ecosystems, biodiversity, and public health worldwide. Rivers, as primary sources of freshwater, are particularly vulnerable to contamination from industrial discharge, domestic sewage, agricultural runoff, and the indiscriminate disposal of solid waste. The accumulation of floating debris, chemical pollutants, and biological contaminants not only degrades water quality but also disrupts aquatic life and endangers communities that depend on rivers for drinking water and irrigation [1].

In India, approximately 70% of surface water bodies are contaminated, with rivers such as the Ganges, Yamuna, and Cauvery facing severe pollution [2]. Traditional water monitoring approaches rely heavily on manual sampling and periodic laboratory analysis. While these methods provide accurate readings, they are time-consuming, expensive, and fail to capture dynamic pollution events such as sudden industrial discharge or heavy rainfall contamination. This delay between data collection and analysis significantly reduces the ability to respond promptly to pollution emergencies.

Existing robotic cleaning systems address surface waste removal but typically treat monitoring and cleaning as separate processes, resulting in operational inefficiencies and incomplete environmental assessment. Most systems lack real-time sensor integration, limiting their effectiveness for comprehensive river management [3][4]. Furthermore, the absence of live visual surveillance in conventional systems reduces situational awareness, preventing the identification of visible pollution sources.

To overcome these limitations, this paper presents Hydro Guard, an IoT-based autonomous river cleaning robot that integrates real-time water quality monitoring, live video surveillance, automated surface waste collection, and remote-controlled navigation into a single unified platform. The system is designed to operate continuously, providing instant environmental data and visual feedback, enabling early detection of contamination and timely intervention.

Main Contributions:

- Development of an integrated IoT-based river cleaning robot using ESP32 microcontroller with multi-sensor environmental monitoring.
- Integration of live video surveillance using ESP32-CAM for real-time visual river inspection.

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- Design and implementation of a PC-based control interface enabling simultaneous remote monitoring and boat navigation.
- Field validation of the system in river environments of Tamil Nadu, India, confirming 95% sensor accuracy and less than 1% navigation error.

II. RELATED WORK

Several research efforts have explored robotic systems for water body cleaning and monitoring. This section reviews key studies relevant to the proposed Hydro Guard system, summarized in Table I below.

Annapurna et al. [1] presented a wireless river cleaning robot designed to safely remove floating waste using remote control, demonstrating the viability of wireless operation. However, the system was limited to surface-level collection and was susceptible to communication signal interference. Zareena et al. [2] proposed a robotics-assisted plastic waste recovery system for rivers and shorelines, improving efficiency over manual methods, but the approach was specific to plastic waste and could not handle dissolved contaminants.

Govindaraj et al. [3] developed a water surface cleaning robot emphasizing simplicity and cost-effectiveness, but it lacked real-time monitoring capabilities essential for data-driven environmental management. Mukherjee et al. [4] conducted experimental design and testing of a water surface cleaning robot, providing valuable performance benchmarks, yet the system lacked integration with intelligent monitoring technologies.

Chandrasekaran et al. [5] introduced an autonomous robotic boat for marine pollution control, reducing human intervention through autonomous navigation. Despite its large-scale applicability, the system involved high complexity and did not incorporate water quality sensing. Premkumar et al. [6] designed an intelligent wireless cleaning robot for ponds and lakes, effective for smaller water bodies but limited by communication range constraints. Das et al. [7] proposed an aquatic robot using recycled materials for both trash removal and basic monitoring, promoting sustainability, though durability and monitoring depth were compromised.

TABLE I — Summary of Related Work on River and Water Cleaning Robots

Study / Authors	Focus Area	Key Merits	Key Demerits
Wireless River Cleaning Robot (Annapurna et al., 2025)	Wireless removal of floating waste	Safe remote operation	Limited to surface; signal dependent
Robotics-Assisted Plastic Waste Recovery (Zareena et al., 2025)	Robotic plastic removal from rivers	Efficient plastic recovery	Limited waste types; environment-sensitive
Water Surface Cleaning Robot (Govindaraj et al., 2025)	Automated surface waste collection	Cost-effective for small bodies	No real-time monitoring
Design and Testing WSC Robot (Mukherjee et al., 2025)	Experimental water surface cleaning	Validated performance	Variable with environment

In contrast to the above studies, the proposed Hydro Guard system addresses these limitations by integrating real-time multi-parameter water quality monitoring, live visual surveillance, autonomous navigation, and surface cleaning into a single, cost-effective platform. This comprehensive integration distinguishes it from all prior approaches.

III. SYSTEM ARCHITECTURE AND METHODOLOGY

A. System Overview

The Hydro Guard system consists of five major operational modules: (1) environmental data acquisition, (2) surface navigation and waste collection, (3) live video surveillance, (4) wireless data transmission, and (5) PC-based monitoring and control. The hardware architecture integrates an ESP32 microcontroller as the central processing unit, interfaced with

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pH, temperature (DHT11/DHT22), turbidity, and GPS sensors for comprehensive water and environmental parameter monitoring. An ESP32-CAM module provides real-time video streaming. A motor driver (L298N) controls four DC motors for directional navigation, and a mechanical dust collector unit removes floating surface waste. All data is transmitted wirelessly to a PC-based interface for remote monitoring and control.

B. Hardware Components

Table II presents the key hardware components used in the Hydro Guard system along with their specifications and functions.

TABLE II — Hardware Components and Specifications

Component	Specification	Function in System
ESP32 Microcontroller	Main processing and Wi-Fi/Bluetooth control unit	Central controller for all modules
ESP32-CAM Module	OV2640 2MP camera with Wi-Fi streaming	Live video surveillance
pH Sensor	Electrochemical pH measurement (0–14 range)	Water acidity/alkalinity monitoring
DHT11/DHT22 Temperature Sensor	Digital temperature measurement, ±0.5°C accuracy	Water and ambient temperature monitoring
Turbidity Sensor	Optical particle detection in water	Water clarity and pollution detection
GPS Module	Real-time geographic position tracking	Location-based monitoring
L298N Motor Driver	Dual H-bridge for DC motor control	Propulsion and directional navigation
DC Motors (×4)	High-torque waterproof motors	Boat movement and navigation
Buzzer	Active buzzer for alert signals	Abnormal condition notifications
LCD Display	16×2 character display	Local sensor data readout
Power Supply / Battery	12V rechargeable battery pack	Onboard power source

Temperature and humidity are measured using DHT11/DHT22 sensors with ±0.5°C accuracy. The turbidity sensor uses optical scattering to detect suspended particles, providing a qualitative measure of water clarity. GPS coordinates are captured using a serial GPS module, enabling location-based monitoring and mapping of pollution distribution across the river.

C. Navigation and Waste Collection

The propulsion system employs four DC motors controlled via the L298N motor driver, enabling forward, reverse, left, and right navigation. The control interface sends directional commands wirelessly, allowing precise boat positioning. The integrated dust collector mechanism operates continuously during navigation, gathering floating waste such as plastics, leaves, and lightweight debris into a removable storage compartment. The boat hull is designed for stability in still water and mild currents, with a waterproof enclosure protecting electronic components.

D. Wireless Communication and Control

The collected sensor data is transmitted wirelessly using the ESP32's built-in Wi-Fi (IEEE 802.11 b/g/n). The ESP32-CAM streams live video over the same Wi-Fi network to the PC interface. Bidirectional communication enables simultaneous data uplink and control command downlink, with an effective range of up to 50 metres in open environments. Error-handling mechanisms maintain data integrity, and an active buzzer alerts users when monitored parameters exceed predefined thresholds.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. Navigation and Dust Collection Performance

The navigation system was evaluated under still water, mild current, and moderate surface disturbance conditions. Results

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indicate stable directional control with less than 1% error in still water and approximately 2% drift under mild currents. The dust collection mechanism achieved approximately 90% removal efficiency for lightweight surface debris such as plastic bags and leaves, and approximately 55% efficiency for larger or denser waste materials. The system demonstrated reliable continuous operation without compromising the monitoring functions, confirming its dual-purpose effectiveness.

B. Real-Time Water Quality Monitoring

Continuous monitoring of pH, temperature, and turbidity was validated against laboratory reference instruments. The system achieved sensor accuracy within 95% of laboratory standards across all three parameters, with pH readings showing ±0.2 deviation, temperature within ±0.5°C, and turbidity within 5% of reference values. Real-time data latency between collection and display was less than 500 milliseconds, ensuring users receive timely information for decision-making. The system successfully detected simulated contamination events — such as the introduction of acidic or turbid solutions — with immediate parameter deviation alerts.

C. Live Video Surveillance Evaluation

The ESP32-CAM-based surveillance system delivered continuous video streaming with a latency of approximately 200 milliseconds under standard conditions. Video clarity was rated at 94% under daylight conditions, with minor degradation observed in low-light environments or under direct sunlight glare. The live feed enabled users to identify visible pollutants including floating debris, surface discoloration, and oil films that complemented sensor data readings. Signal quality remained stable within 30 metres, with minor degradation beyond 40 metres in outdoor open-water environments.

D. Wireless Communication Analysis

The wireless communication system maintained stable connectivity with less than 0.5% packet loss in open-water environments up to 50 metres range. In conditions with obstacles or extended distances, packet loss increased to approximately 3%, resulting in minor control delays. Error-handling protocols ensured system recovery without major operational disruption. Bidirectional communication between the boat and PC interface functioned seamlessly, supporting simultaneous sensor data uplink and navigation command downlink.

Table III presents a comprehensive summary of all evaluated performance metrics for the Hydro Guard system.

TABLE III — Hydro Guard System Performance Results

Parameter / Module	Performance Observed	Accuracy / Error Rate	Reliability
Navigation (Still Water)	Stable & controlled	< 1% directional error	High
Navigation (Mild Current)	Stable with minor drift	~2% directional error	High
pH Monitoring	Continuous real-time	±0.2 pH (vs. lab)	High
Temperature Monitoring	Continuous real-time	±0.5°C (vs. lab)	High
Turbidity Monitoring	Continuous real-time	Within 5% of lab results	High
Dust Collection (Light Debris)	Efficient collection	~90% debris removed	High
Dust Collection (Large Debris)	Partial collection	~55% debris removed	Moderate
Live Video Streaming	Low latency (~200ms)	94% clarity (daylight)	High
Wireless Communication (Open)	Stable up to 50m	< 0.5% packet loss	High
Wireless Communication (Obstacles)	Minor degradation	~3% packet loss	Moderate

Parameter / Module	Performance Observed	Accuracy / Error Rate	Reliability
Overall System Sensor Accuracy	95% vs laboratory	< 1% error rate	High

E. Comparative Analysis with Existing Systems

Table IV provides a structured comparison of the Hydro Guard system against key prior works across critical functional dimensions. The proposed system is the only solution offering all four capabilities simultaneously: surface cleaning, real-time water quality monitoring, live surveillance, and autonomous navigation. This integration directly addresses the fragmented approach observed in all reviewed prior systems.

TABLE IV — Comparative Analysis of Hydro Guard vs. Existing Systems

System	Surface Cleaning	Water Quality	Live Surveillance	Autonomous Nav.	Remarks
Annapurna et al. [1]	✓	✗	✗	✗	Wireless control only
Zareena et al. [2]	✓	✗	✗	✗	Plastic-specific
Govindaraj et al. [3]	✓	✗	✗	✗	No monitoring
Chandrasekaran et al. [5]	✓	✗	✗	✓	No water quality sensing
Das et al. [7]	✓	✓	✗	✗	Recycled materials
Proposed Hydro Guard	✓	✓	✓	✓	**Fully integrated system**

V. CONCLUSION AND FUTURE WORK

This paper presents Hydro Guard, an IoT-based intelligent river cleaning robot that successfully integrates real-time water quality monitoring, live video surveillance, autonomous surface cleaning, and remote navigation into a single unified platform. The system effectively addresses the critical limitations of traditional and existing robotic approaches, which typically treat monitoring and cleaning as separate, disconnected processes. Field validation in Tamil Nadu, India confirmed that the system achieves sensor accuracy within 95% of laboratory standards with less than 1% navigation error. The live video streaming system delivered low-latency visual feedback, enhancing situational awareness and enabling identification of visible pollution sources that sensor data alone cannot detect.

The integrated dust collection mechanism demonstrated high efficiency for lightweight surface debris, while the wireless communication system maintained reliable bidirectional data exchange.

The proposed system offers significant advantages including continuous automated monitoring, early pollution detection, reduction of human presence in hazardous environments, and cost-effective implementation. These features collectively contribute to more proactive and effective river pollution management.

Future work will focus on: (i) integrating machine learning algorithms for predictive water quality analysis and anomaly classification; (ii) expanding sensor arrays to include dissolved oxygen and chemical oxygen demand (COD) sensors; (iii) implementing solar-powered nodes for sustainable long-duration operation; (iv) deploying swarm robotics for coordinated multi-robot coverage of large river areas; and (v) developing a cloud-based data platform with historical trend analysis and automated authority notification systems.

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