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Design and Simulation of a Low Cost IoT Enabled Autonomous River Cleaning Robot for Small-Scale Environmental Applications

I. Ismail[1], D. I. A. Mu'izz[1], I. Ismail[2]

[1]Department of Electrical Engineering, Politeknik Sultan Salahuddin Abdul Aziz Shah, 40150 Shah Alam, Selangor, Malaysia.
[2]Department of Electrical Engineering, Politeknik Bagan Datuk, 36100 Bagan Datuk, Perak, Malaysia.

Corresponding Author's Email: [1]ilya@psa.edu.my
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ABSTRACT – This paper presents the design, simulation, and preliminary prototype development of a low-cost Internet of Things (IoT)-enabled autonomous river cleaning robot for small-scale environmental applications. River pollution in Malaysia necessitates efficient and safer cleaning solutions beyond conventional manual methods, which are labour-intensive and lack real-time monitoring capability. The proposed system integrates an ESP32 microcontroller, an ultrasonic sensor for waste detection, DC motors for navigation, and a conveyor mechanism for debris collection. The system operates in a semi-autonomous mode with real-time monitoring capability. The system was evaluated through simulation and initial prototype testing under controlled conditions. The results demonstrate that the system is capable of detecting objects and activating the cleaning mechanism based on a predefined threshold. However, limitations were observed during prototype testing, particularly in motor torque capability and structural stability when handling collected debris, which affected consistent operation under load conditions. Overall, the study validates the functional feasibility of the proposed design, while highlighting key engineering challenges that must be addressed before real-world deployment. Future work will focus on improving motor performance, structural stability, and system robustness for outdoor environmental applications.

KEYWORDS : IoT-based river cleaning, Autonomous robot, Ultrasonic sensor, Environmental monitoring

1.0 INTRODUCTION

Rivers play a critical role in supporting ecological balance, water resources, and socio-economic activities in Malaysia. However, increasing urbanization, industrial activities, and improper solid waste disposal have significantly contributed to river pollution, particularly in major waterways such as the Klang River and Sungai Skudai [1], [2]. The accumulation of floating waste, including plastics and non-biodegradable materials, not only degrades water quality but also disrupts aquatic ecosystems, increases flood risks, and poses health hazards to surrounding communities [3][. Conventional river cleaning methods in Malaysia primarily rely on manual labour using nets and boats. While these methods are still widely practiced, they are labour-intensive, time-consuming, and expose workers to unsafe and contaminated environments[1]. In addition, manual approaches lack real-time monitoring capabilities, resulting in reactive rather than proactive environmental management[2]. This limitation highlights the need for more efficient, safer, and technology-driven solutions to support river cleaning operations.

Recent advancements in Internet of Things (IoT) and embedded systems have enabled the development of smart environmental monitoring and automation systems. Several studies have explored the use of autonomous robots and IoT-based platforms for waste collection and monitoring in aquatic environments[4], [5], [6], [7]. However, most existing solutions are designed for large-scale applications, involve high implementation costs, or are not suitable for narrow and shallow river conditions commonly found in Malaysia[6], [7], [8]. Furthermore, many systems remain at the conceptual or experimental stage and lack practical validation in simplified, scalable designs[5], [9].

Therefore, this study proposes the design and simulation of a low-cost IoT-enabled autonomous river cleaning robot developed as a student-based prototype. The system integrates an ESP32 microcontroller, ultrasonic sensors, DC motors, and a conveyor mechanism to enable semi-autonomous waste detection and collection, while providing real-time monitoring through IoT platforms. The study aims to evaluate the functionality and effectiveness of the system in a controlled simulation environment before physical implementation. In addition to addressing environmental challenges, this study also serves as a practical platform for engineering education, allowing students to apply knowledge in IoT, embedded systems, and robotics in a real-world context. The proposed system contributes to sustainable environmental management and aligns with the United Nations Sustainable Development Goals (SDG), particularly SDG 6 (Clean Water and Sanitation), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action).

1.1 Existing River Cleaning Technologies

Various river cleaning technologies have been developed to address the increasing issue of floating waste pollution[5], [7], [8], [9], [10]. These systems range from manual collection methods to semi-automated and fully autonomous robotic solutions. Large-scale systems such as The Ocean Cleanup's Interceptor utilize solar-powered conveyor mechanisms to continuously collect debris with minimal human intervention[4]. While effective in high-volume waste environments, such systems are costly and not suitable for narrow or shallow rivers commonly found in Malaysia[8]. Other advanced systems, such as the SMURF autonomous robot, incorporate navigation algorithms, sensor integration, and coverage planning for efficient waste collection [6]. However, these systems are typically complex and require high implementation costs, limiting their applicability for small-scale or community-level deployment.

In contrast, several IoT-based river cleaning robots have been proposed in recent studies, focusing on reducing manual labour through basic automation and remote monitoring[4], [5], [10]. Although these systems demonstrate potential, many are still in early development stages and lack scalability, adaptability, and consistent real-world validation as shown in Table 1.

Table 1. Comparison of Existing River Cleaning Technologies

Technology/ System	Key Features	Advantages	Limitations	Suitability
Manual Cleaning Method	Use of nets and boats operated by workers	Low cost, simple implementation	Labour-intensive, unsafe, no real-time monitoring	Small-scale but inefficient
Ocean Cleanup Interceptor [7]	Solar-powered, conveyor-based automated waste collection	High efficiency, autonomous operation	Very high cost, large size	Large rivers only
SMURF Autonomous Robot [6]	GPS navigation, path planning, autonomous control	Advanced navigation and coverage	Complex system, expensive	Research-scale implementation
IoT-Based Cleaning Robot [9], [10]	Sensor-based detection, IoT monitoring	Remote monitoring, reduced manpower	Limited scalability, early-stage development	Small to medium scale
IR Sensor-Based Systems [11]	Infrared-based object detection	Low cost, simple design	Affected by sunlight and reflection	Indoor / controlled environment
Proposed Study System	Ultrasonic based object detection	Low cost, reliable detection, real-time monitoring	Limited to prototype stage	Small-scale, educational and local deployment

The comparison in Table 1 highlights that while existing river cleaning technologies demonstrate significant advancements in automation and environmental monitoring, many solutions are either too complex, costly, or unsuitable for small-scale deployment. Large-scale systems such as the Interceptor offer high efficiency but lack adaptability to local river conditions. On the other hand, simpler IoT-based systems provide flexibility but often suffer from limitations in sensor accuracy and system scalability. Therefore, there is a clear need for a balanced solution that integrates reliability, affordability, and practical applicability. The system proposed in this study addresses these gaps by combining a low-cost hardware configuration with improved sensor selection and IoT-based monitoring, making it suitable for both educational and localized environmental applications.

Ultrasonic sensing is selected in this study due to its robustness in outdoor river environments compared to optical-based sensors[12]. Infrared sensors are highly sensitive to ambient light, water surface reflection, and environmental glare, which can result in inaccurate detection in open environments[11]. In contrast, ultrasonic sensors operate based on sound wave propagation, making them less affected by lighting conditions and more suitable for detecting floating debris.

Nevertheless, ultrasonic sensing also presents limitations in outdoor applications. Detection accuracy may be influenced by irregular water surfaces, floating objects of varying shapes, and environmental disturbances[12]. These factors may lead to fluctuations in distance readings, particularly near threshold boundaries. Therefore, further enhancement such as signal filtering or sensor fusion is required for improved robustness.

2.0 METHODOLOGY

2.1 System Overview and Design Approach

This study adopts a design and simulation approach to develop an IoT enabled autonomous river cleaning robot. The system is designed as a prototype in an academic setting to evaluate its functional capability and effectiveness in detecting and collecting floating waste in a controlled environment. The development process consists of system design, component integration, circuit simulation, and functional validation. The overall system integrates sensing, processing, actuation, and communication modules. The ESP32 microcontroller acts as the central processing unit, receiving input data from sensors, executing control logic, and transmitting system information to a cloud based IoT platform. The design emphasizes low-cost implementation, modularity, and ease of replication for educational and small-scale environmental applications.

2.2 System Architecture

Figure 1 illustrates the overall system architecture of the proposed IoT-based river cleaning robot. The system is centered around the ESP32 microcontroller, which acts as the main processing unit. Input from the ultrasonic sensor is used to detect floating waste and obstacles, and the data is processed to determine the appropriate system response.

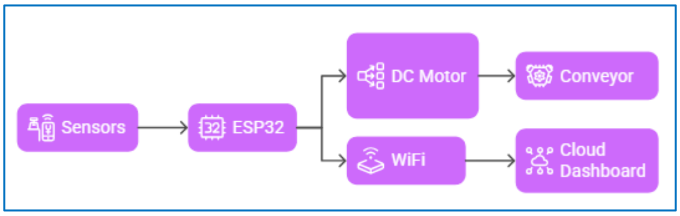

Figure 1. Block Diagram of the Proposed IoT-Based River Cleaning Robot

Based on the processed signal, the ESP32 controls the L298N motor driver, which in turn activates the DC motors for movement and the conveyor mechanism for waste collection. At the same time, the system transmits operational data to an IoT platform such as Blynk or Firebase, allowing real-time monitoring of the robot's status. This integrated architecture enables the system to perform semi-autonomous cleaning while maintaining user accessibility through remote monitoring.

The system operates using a regulated supply voltage of 5V for the ESP32 microcontroller and sensors, while the DC motors are powered using a separate 7.4V–12V supply through the L298N motor driver. This separation ensures stable operation of the control unit while allowing sufficient power for motor actuation.

For object detection, the ultrasonic sensor is configured with an effective detection range between 2 cm and 400 cm. In this study, a threshold distance of approximately 15 cm is defined to trigger the cleaning mechanism. When an object is detected within this range, the system interprets it as floating debris and activates the appropriate response. This threshold is selected to balance detection sensitivity and avoid false triggering due to minor surface disturbances.

2.3 System Operation Flow

The operational flow of the system is presented in Figure 2. The process begins with system initialization and Wi-Fi connection to enable communication with the IoT platform.

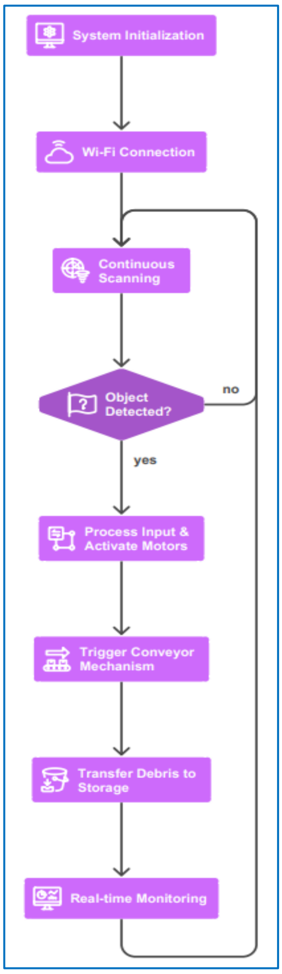

Figure 2. Flowchart of the System Operation

Once connected, the ultrasonic sensor continuously scans the surrounding environment for floating debris. If an object is detected within a predefined distance threshold of approximately 15 cm, the ESP32 processes the input and activates the DC motors to adjust movement while simultaneously triggering the conveyor mechanism to collect the waste. The collected debris is transferred into a storage compartment. If no object is detected, the system continues scanning and navigation. This process is repeated continuously, allowing the robot to operate in a semi-autonomous mode while providing real-time monitoring to the user.

2.4 Simulation Setup and Implementation

Figure 3 shows the Proteus simulation of the proposed river cleaning robot system. The simulation includes the ESP32 microcontroller, ultrasonic sensor module, L298N motor driver, and DC motors configured to replicate the system design.

The simulation was conducted to validate the logical interaction between sensor input and motor response. When the ultrasonic sensor detects an object, the ESP32 processes the signal and generates control outputs to activate the motor driver. This results in the movement of the robot and activation of the conveyor mechanism, demonstrating the intended system behavior. Although the simulation successfully verifies the control logic and component interaction, certain limitations were observed. The motor speed appeared lower than expected, which can be attributed to the constraints of the Proteus simulation environment in accurately representing real-world electrical load and mechanical resistance. Therefore, while the simulation confirms system feasibility, further validation through physical prototyping is required to evaluate actual performance.

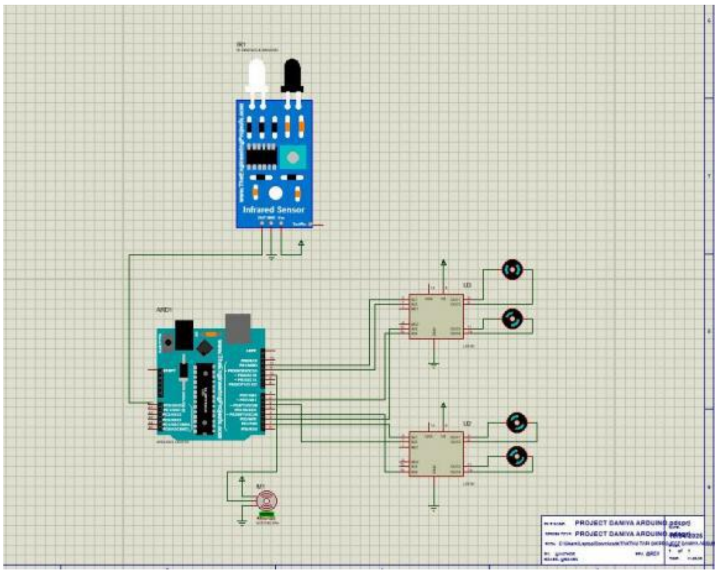

Figure 3. Proteus Simulation of the Proposed System

2.5 System Validation Approach

The validation of the system is carried out through functional testing within the simulation environment. The evaluation focuses on the ability of the system to detect objects accurately, respond to sensor input, and activate the appropriate mechanical actions. Particular attention is given to the consistency of the control logic and the coordination between sensing and actuation components.

While the simulation confirms that the system operates according to the intended design, it does not fully reflect real world operating conditions. Factors such as water flow, environmental disturbances, and hardware limitations are not fully represented in the simulation environment.

Therefore, further validation through physical prototyping and field testing is necessary to assess the actual performance and reliability of the system.

3.0 RESULTS AND DISCUSSION

3.1 System Functionality and Response

The functionality of the proposed system was evaluated through simulation using Proteus Design Suite. The primary objective of this simulation was to verify the interaction between the ultrasonic sensor, ESP32 microcontroller, and motor driver in executing the intended control logic.

The simulation results indicate that the system is capable of detecting objects within the predefined threshold distance and responding accordingly. When an object is detected within approximately 15 cm, the ultrasonic sensor successfully transmits the signal to the ESP32, which processes the input and activates the motor driver. This results in the movement of the DC motors and the activation of the conveyor mechanism, demonstrating the intended waste collection behavior.

The system also shows consistent operation in continuous scanning mode, where the sensor repeatedly monitors the environment and triggers responses based on detection conditions. This confirms that the control logic implemented in the system is stable and capable of supporting semi-autonomous operation.

3.2 Simulation Performance Analysis

Although the simulation validates the functional behavior of the system, certain performance limitations were observed. One of the most noticeable issues is the reduced speed of the DC motors during operation. Despite correct signal transmission from the ESP32 to the motor driver, the motor response appears slower than expected.

This limitation is primarily attributed to the constraints of the Proteus simulation environment, which does not fully replicate real-world electrical characteristics such as current delivery, pulse-width modulation (PWM) behavior, and mechanical load resistance. As a result, the simulation provides an approximation of system behavior rather than an exact representation of physical performance. Nevertheless, the simulation remains effective in validating the logical interaction between system components, ensuring that the sensing, processing, and actuation mechanisms function as intended.

3.3 Prototype Validation

To further validate the simulation findings, a scaled prototype was developed and tested under controlled conditions. The prototype integrates the ESP32 microcontroller, ultrasonic sensor, motor driver, and conveyor mechanism to replicate the proposed system design.

The prototype testing demonstrates that the system is capable of detecting objects within the predefined threshold and activating the cleaning mechanism accordingly. The ultrasonic sensor provides consistent detection performance, and the control logic successfully triggers motor and conveyor operations in response to detected objects. However, several limitations were observed during testing. The DC motors used in the prototype exhibited insufficient torque when handling collected debris, resulting in reduced movement efficiency. In addition, the structural stability of the prototype was affected when lifting and accumulating waste, leading to minor imbalance during operation. These limitations impacted the system’s ability to maintain consistent performance under load conditions.

These findings indicate that while the sensing and control mechanisms are functioning as intended, the mechanical design and actuation components require further optimization.

Improvements in motor capacity, structural reinforcement, and load distribution are necessary to enhance system stability and reliability for real-world river environments.

3.4 System Behaviour and Performance Metrics

Based on both simulation results and controlled prototype testing, the system performance was further analysed through functional behaviour and measurable engineering indicators. Table 2 presents the system behaviour under different operating conditions, while Table 3 summarizes the corresponding quantitative performance metrics.

Table 2. System Functional Behaviour under Different Conditions

Scenario	Distance Detected (cm)	System Response	Motor Status	Conveyor Status	Observation & Remarks
No object detected	> 20 cm	Idle scanning	OFF	OFF	System stable. Normal idle operation
Object detected (far range)	15 – 20 cm	Detection without activation	ON (low response)	OFF	System stable. Detection valid but not within trigger range
Object detected (trigger zone)	≤ 15 cm	Activate cleaning system	ON	ON	System stable. System responds as designed
Continuous detection	≤ 15 cm (repeated)	Continuous cleaning	ON	ON	System stable. Consistent loop operation
Distance fluctuation	10 – 18 cm	Intermittent response	ON/OFF	ON/OFF	Minor instability due to threshold sensitivity
Prototype under load	≤ 18	Reduced performance	ON (Slight delay)	Slight delay	Reduced performance due to motor torque limitation and structural instability

Tables 2 and 3 provide a clearer interpretation of the system behaviour and performance under different operating conditions. The results can be classified into three main operational states: idle condition, optimal operation, and unstable condition.

Table 3. System Performance Metrics Based on Simulation and Prototype Testing

Scenario	Distance Detected (cm)	Detection Accuracy (%)	False Trigger Rate (%)	Response Time (s)
No object detected	> 20 cm	100	0	0.5
Object detected (far range)	15 – 20 cm	95	5	1.0
Object detected (trigger zone)	≤ 15 cm	96.7	3.3	1.3
Continuous detection	≤ 15 cm (repeated)	96	4	1.2
Distance fluctuation	10 – 18 cm	85	15	1.5
Prototype under load	≤ 18	88	12	1.6

Under idle conditions, where no object or distant objects are detected beyond the predefined threshold, the system remains stable with both motor and conveyor mechanisms inactive. This indicates that the system successfully avoids unnecessary activation. As shown in

Table 3, the idle condition records 100% detection accuracy, zero false trigger rate, and the shortest response time, indicating stable baseline operation.

During optimal operation, where objects are detected within the trigger threshold of approximately 15 cm, the system activates both the motor and conveyor mechanisms as intended. The detection accuracy remains above 96%, while the false trigger rate remains low. This confirms that the sensing and control logic operate effectively under normal detection conditions. The continuous detection condition also shows that the system can maintain repeated operation without major interruption.

In unstable conditions, performance degradation is observed. The distance fluctuation condition shows intermittent activation due to sensitivity near the threshold boundary, while the prototype under load condition highlights reduced motor performance and slight delay. These findings are consistent with the limitations observed during prototype testing, where insufficient motor torque and structural imbalance affected stable operation when handling collected debris.

Overall, the results show that the proposed system performs reliably under controlled and optimal conditions, but further improvement is required under dynamic and load conditions. The analysis indicates that threshold optimization, signal filtering, stronger motor selection, and improved structural design are necessary before the system can be tested in real outdoor river environments. This classification-based interpretation strengthens the reliability of the analysis by linking system behaviour to measurable performance indicators under different operating conditions.

4.0 CONCLUSION

This study presents the design and simulation of a low-cost IoT-enabled autonomous river cleaning robot developed as a prototype in an academic setting. The proposed system integrates an ESP32 microcontroller, ultrasonic sensor, DC motors, and a conveyor mechanism to perform semi-autonomous detection and collection of floating waste. The simulation results confirm that the system is able to detect objects within a predefined threshold and activate the appropriate cleaning response. The interaction between sensing, processing, and actuation components operates as intended, demonstrating the feasibility of the proposed system design.

However, certain limitations were observed, particularly in terms of motor performance and response stability under fluctuating detection conditions, which are mainly attributed to constraints of the simulation environment. While the system demonstrates functional feasibility in terms of sensing and control logic, prototype testing reveals important limitations in mechanical performance, particularly in motor torque and structural stability under load conditions. Therefore, the current implementation should be considered as a preliminary prototype rather than a fully deployable system.

Future work will focus on improving motor capacity, enhancing structural design, and conducting testing in real outdoor river environments to evaluate long-term reliability and system robustness.

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