An AI-Driven IoT-Enabled Autonomous System for Water Surface Waste Collection

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ABSTRACT

The rapid increase in plastic and solid waste accumulation on water surfaces has emerged as a serious environmental challenge, posing significant threats to aquatic ecosystems, water quality, and public health. Rivers, lakes, and reservoirs frequently act as collection points for floating debris due to improper waste disposal practices, urban runoff, and industrial activities. Conventional water surface cleaning methods are largely manual, labor-intensive, time-consuming, and unsafe for continuous operation, making them inefficient for large-scale deployment. Therefore, there is a growing need for intelligent, automated solutions capable of performing waste detection and collection with minimal human intervention.

This paper presents an AI-driven, IoT-enabled autonomous system for water surface waste collection, designed to detect, collect, and monitor floating plastic waste in real time. The proposed system integrates an ESP32-CAM module for real-time image acquisition and employs the YOLOv5 deep learning algorithm for accurate detection and classification of floating waste objects. An Arduino UNO microcontroller acts as the central control unit, coordinating motor control, navigation, and conveyor-based waste collection mechanisms. IoT connectivity using a Wi-Fi module enables remote monitoring of system performance and environmental parameters such as temperature and humidity, supporting data-driven environmental management.

The system was implemented and tested in controlled water environments to evaluate detection accuracy, response time, and collection efficiency. Experimental results indicate that the proposed system achieves high waste detection accuracy with minimal processing latency and effective waste collection using a motor-driven conveyor mechanism. The autonomous operation significantly reduces human effort and operational risks while improving cleaning efficiency. The use of low-cost and readily available components makes the system economically feasible and scalable for deployment in various water bodies.

Overall, the proposed AI-driven autonomous system provides a practical, efficient, and sustainable solution for water surface waste management and demonstrates the potential of integrating Artificial Intelligence and Internet of Things technologies for environmental protection and pollution control.

INTRODUCTION

Water pollution has emerged as one of the most critical environmental challenges faced by modern society. Rapid urbanization, industrial expansion, population growth, and improper waste disposal practices have significantly increased the amount of solid waste entering natural water bodies such as rivers, lakes, reservoirs, canals, and coastal regions. Among various types of pollutants, plastic waste and floating solid debris pose a severe threat to aquatic ecosystems, water quality, and human health. Due to their non-biodegradable nature, plastics persist in water bodies for decades, breaking down into microplastics that further contaminate the environment and enter the food chain.

Floating waste accumulation disrupts aquatic ecosystems by blocking sunlight penetration, reducing dissolved oxygen levels, and damaging habitats of aquatic flora and fauna. Aquatic animals often ingest plastic debris, leading to severe health issues or death. In addition, polluted water bodies become breeding grounds for disease-causing microorganisms, increasing the risk of waterborne diseases such as cholera, dysentery, and typhoid. From an economic perspective, polluted rivers and lakes negatively impact fisheries, tourism, and potable water resources, thereby affecting both livelihoods and public infrastructure.

Traditional water surface cleaning methods primarily rely on manual labor or manned boats equipped with basic mechanical collection mechanisms. These approaches are highly labor-intensive, time-consuming, and costly, especially when deployed over large water bodies. Furthermore, manual cleaning exposes workers to health hazards associated with contaminated water and unsafe working conditions. Such methods are also inefficient for continuous monitoring and cleaning, as they depend on human availability and weather conditions. As a result, conventional systems fail to provide a scalable and sustainable solution to the growing problem of water surface pollution.

In recent years, advancements in automation, embedded systems, and robotics have paved the way for the development of autonomous surface vehicles (ASVs) capable of performing environmental monitoring and cleaning tasks. These systems reduce human involvement and enable continuous operation with improved efficiency. However, many early autonomous cleaning systems relied on basic sensors such as ultrasonic or infrared sensors, which lack the intelligence required to accurately identify waste objects. As a result, these systems often suffer from false detections and inefficient waste collection.

The emergence of **Artificial Intelligence (AI)**, particularly in the field of computer vision, has significantly improved object detection and classification capabilities. Deep learning algorithms such as Convolutional Neural Networks (CNNs) enable machines to recognize complex visual patterns with high accuracy. Among various object detection models, the **You Only Look Once (YOLO)** family of algorithms has gained widespread popularity due to its real-time detection capability and high accuracy. YOLOv5, in particular, offers a balance between detection performance and computational efficiency, making it suitable for deployment on embedded and edge computing platforms.

At the same time, the **Internet of Things (IoT)** has revolutionized environmental monitoring by enabling seamless communication between sensors, devices, and cloud platforms. IoT technology allows real-time data collection, remote monitoring, and centralized control of distributed systems. In the context of water pollution management, IoT enables continuous monitoring of system performance and environmental parameters such as temperature, humidity, and operational status. This data-driven approach supports timely decision-making and effective pollution control strategies.

By integrating AI-based vision systems with IoT-enabled communication and embedded control, autonomous water surface waste collection systems can achieve higher efficiency, accuracy, and scalability. Such systems are capable of detecting floating waste in real time, navigating autonomously, collecting debris, and transmitting operational data to remote monitoring platforms. This integration not only reduces human effort but also enhances operational safety and reliability.

This paper proposes an **AI-driven, IoT-enabled autonomous system for water surface waste collection**, designed to address the limitations of traditional cleaning methods. The proposed system utilizes an ESP32-CAM module for real-time image acquisition and employs the YOLOv5 deep learning algorithm for accurate detection and classification of floating plastic waste. An Arduino UNO microcontroller serves as the central control unit, coordinating motor operation, navigation, and a conveyor-based waste collection mechanism. IoT connectivity using a Wi-Fi module enables real-time monitoring of environmental conditions and system performance.

The proposed system aims to provide a low-cost, modular, and scalable solution suitable for deployment in rivers, lakes, ponds, and reservoirs. By automating the waste detection and collection process, the system significantly reduces manpower requirements and operational risks. Furthermore, the integration of environmental monitoring supports sustainable water resource management and assists authorities in identifying pollution hotspots.

The remainder of this paper is organized as follows: Section II describes the materials, methods, and system architecture of the proposed system. Section III presents the implementation details along with results and performance analysis. Section IV discusses the advantages, challenges, and limitations of the system. Finally, Section V concludes the paper and outlines possible directions for future enhancements.

LITERATURE REVIEW

Water surface pollution caused by floating plastic and solid waste has attracted increasing research attention in recent years. Early waste collection methods primarily relied on manual cleaning and human-operated boats equipped with basic mechanical tools such as nets and conveyor systems. Although effective for small-scale cleaning, these approaches were labor-intensive, time-consuming, and unsuitable for continuous operation in large water bodies.

With the advancement of embedded systems and robotics, autonomous surface vehicles (ASVs) have been proposed for environmental monitoring and waste collection. Several researchers developed microcontroller-based cleaning boats using predefined navigation paths and basic sensors. While these systems reduced human effort, they lacked intelligent waste detection, resulting in inefficient collection and higher false detections. Computer vision techniques were later introduced to improve waste identification. Initial approaches used traditional image processing methods such as color segmentation and edge detection. However, these techniques were highly sensitive to lighting variations, water reflections, and surface disturbances, limiting their performance in real-world environments.

Recent advancements in deep learning have significantly enhanced object detection capabilities. Convolutional Neural Network (CNN)–based models such as Faster R-CNN, SSD, and YOLO have been widely used for real-time object detection. Among these, YOLO-based algorithms have shown superior performance in terms of speed and accuracy. Studies have demonstrated the effectiveness of YOLO models in detecting floating debris and marine waste. YOLOv5, in particular, offers high detection accuracy with low computational complexity, making it suitable for embedded and edge-based applications. In parallel, Internet of Things (IoT) technologies have been widely adopted for environmental monitoring. IoT-enabled systems allow real-time data transmission, remote monitoring, and centralized control. Several researchers integrated IoT with water quality monitoring systems to measure parameters such as temperature and turbidity. However, many existing solutions focus primarily on monitoring rather than active waste collection.

Despite these developments, limitations such as high system cost, limited autonomy, and incomplete integration of detection, collection, and monitoring functions remain. Most existing systems address only partial aspects of water pollution management. Therefore, there is a need for a low-cost, AI-driven, IoT-enabled autonomous system that provides accurate waste detection, efficient collection, and real-time monitoring.

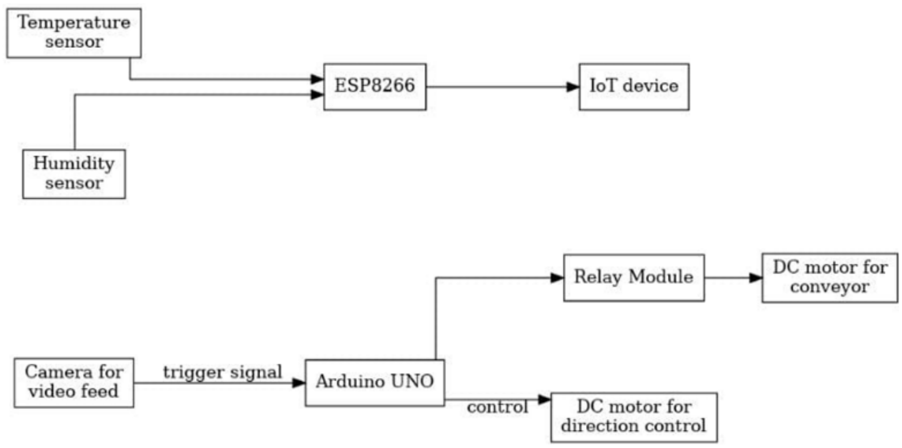
The proposed system addresses these gaps by integrating YOLOv5-based waste detection, embedded control, IoT communication, and a conveyor-based collection mechanism, offering a complete and scalable solution for water surface waste management.

METHODS AND MATERIAL

The proposed autonomous waste collection system is designed to detect, collect, and monitor floating plastic waste on water surfaces using a combination of embedded hardware, AI-based vision processing, and IoT communication technologies.

A. System Overview

The proposed system is an AI-driven, IoT-enabled autonomous water surface waste collection system that integrates sensing, control, and actuation units. Temperature and humidity sensors continuously monitor environmental conditions and transmit the data to an IoT device through the ESP8266 Wi-Fi module for remote monitoring.
A camera module provides live video feed to the Arduino UNO, which acts as the main control unit. Based on the received trigger signal, the Arduino controls a relay module to operate the DC motor driving the conveyor mechanism for waste collection. Another DC motor is used for direction control, enabling autonomous movement of the system on the water surface.



Fig(1): Block Diagram

The integration of IoT-based environmental monitoring with motor-controlled waste collection ensures efficient, autonomous operation with minimal human intervention.
In addition, the system architecture is designed to ensure reliable coordination between sensing, decision-making, and actuation processes. The real-time data obtained from the camera and environmental sensors enables timely control actions, while the modular design allows easy maintenance and future upgrades. The use of wireless communication enhances system flexibility by enabling remote supervision, making the proposed system suitable for continuous deployment in various water bodies.

B. Components Used

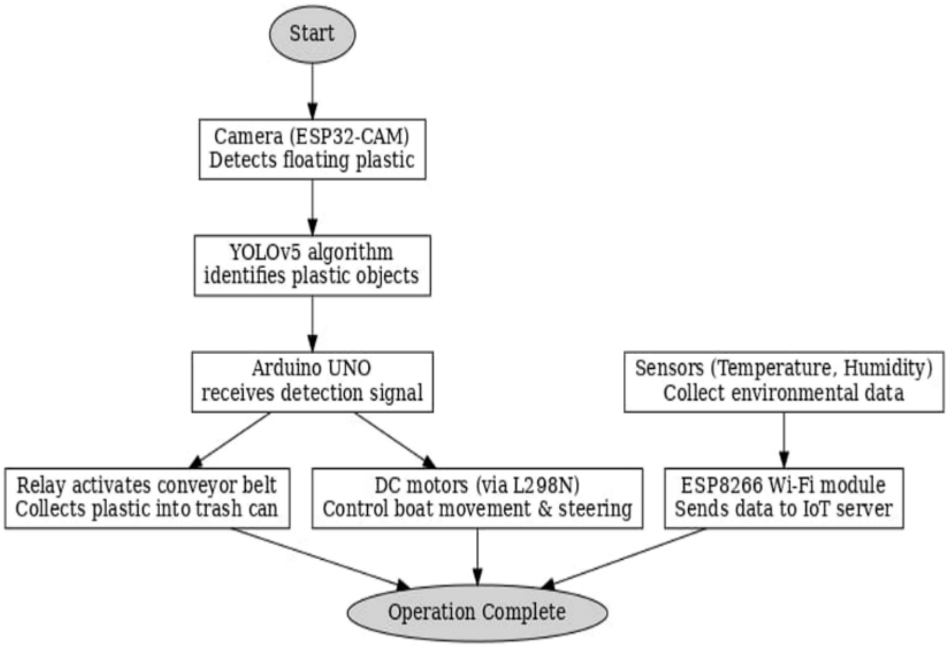
Table 1 summarizes the components employed in the system and their primary functions

Sr. No.	Component Name	Purpose / Function
1	Arduino UNO	Acts as the main control unit; processes sensor inputs and controls motors and relays
2	ESP32-CAM	Captures real-time images of the water surface for AI-based waste detection
3	YOLOv5 Algorithm	Detects and classifies floating plastic waste in real time
4	ESP8266 Wi-Fi Module	Enables IoT-based data transmission and remote monitoring
5	Temperature Sensor	Monitors ambient temperature near the water surface
6	Humidity Sensor	Measures environmental humidity conditions
7	Motor Driver Module	Controls speed and direction of DC motors
8	DC Motors	Provides propulsion and drives the conveyor belt mechanism
9	Relay Module	Safely switches high-power components such as the conveyor motor
10	Conveyor Belt Mechanism	Collects and lifts floating waste into the storage container
11	Battery	Supplies power to the entire system
12	Chassis / Floating Platform	Supports system components and enables movement on the water surface

The selection of low-power and cost-effective components ensures system affordability and scalability for real-world deployment.

C. Operational Flow

The operational process begins with system initialization and sensor calibration. The ESP32-CAM continuously captures images of the water surface, which are analyzed by the YOLOv5 model to identify plastic waste. If waste is detected, the Arduino activates the conveyor belt mechanism to collect the debris. Simultaneously, the boat navigates autonomously while avoiding obstacles.
Detected waste data and system status are transmitted to a remote monitoring platform via IoT connectivity. This continuous loop enables real-time waste collection and monitoring.



Fig(2): Flowchart

During operation, the control unit continuously monitors sensor inputs and system performance to ensure stable functioning. The motor driver regulates the speed and direction of the DC motors based on control signals from the Arduino, allowing smooth navigation on the water surface. In case of temporary communication failure, the system continues autonomous operation and resumes data transmission once connectivity is restored, ensuring uninterrupted waste collection and monitoring.

D. Algorithmic Steps

The algorithm governing the operation of the system can be summarized as follows:

1. Initialize system and power supply
2. Capture real-time images using ESP32-CAM
3. Process images using YOLOv5 model
4. Detect floating plastic waste
5. Activate conveyor mechanism for waste collection
6. Store collected waste onboard
7. Transmit system data via IoT
8. Repeat process continuously

E. Advantages of the Design

The proposed design enables autonomous operation, reduces human intervention, and improves cleaning efficiency. AI-based detection ensures accurate identification of waste, while IoT connectivity allows remote supervision and data logging. The modular architecture supports scalability and easy maintenance.

RESULTS AND DISCUSSION

A. System Implementation and Testing

The autonomous system was implemented and tested in controlled water environments to evaluate its functionality, waste detection accuracy, and collection efficiency. During testing, the ESP32-CAM continuously captured live video of the water surface, and the YOLOv5 deep learning model processed the frames to detect floating plastic waste.

The system was tested under different lighting conditions and varying water surface disturbances to analyze robustness. The conveyor mechanism was activated upon detection and successfully collected floating waste with minimal mechanical delay, demonstrating smooth coordination between detection and actuation units.

B. Performance Analysis

The system exhibited reliable real-time performance with minimal processing latency between waste detection and actuation. The YOLOv5 model achieved satisfactory detection accuracy suitable for practical deployment in surface-level waste collection applications. The Arduino-based control system ensured stable motor operation and precise movement control. IoT-based monitoring enabled real-time observation of system parameters and environmental data, allowing efficient supervision and performance evaluation during operation.

C. Applications and Real-World Impact

The proposed system can be effectively deployed in rivers, lakes, ponds, reservoirs, and canals for continuous water surface waste collection. It reduces the dependency on manual labor and improves cleaning efficiency in polluted water bodies. The system supports environmental agencies and municipal authorities in identifying pollution-prone areas and maintaining water quality. By enabling autonomous operation and real-time monitoring, the system contributes to sustainable waste management and environmental conservation efforts.

D. Discussion of Advantages

The system demonstrates improved detection accuracy, reduced response time, and lower operational cost compared to traditional cleaning approaches. AI-based vision enhances selectivity, while IoT-enabled monitoring supports scalable deployment and centralized supervision.

E. Challenges and Limitations

Despite its advantages, the system has certain limitations. The operational duration is restricted by battery capacity, which limits long-term continuous deployment. Reliable system performance depends on stable network connectivity for IoT-based data transmission. The onboard waste storage capacity is limited, requiring periodic maintenance and unloading. Additionally, environmental factors such as waves, water currents, weather conditions, and lighting variations may affect waste detection accuracy and navigation stability.

CONCLUSION

This paper presented an AI-driven, IoT-enabled autonomous system for efficient water surface waste collection, aimed at addressing the growing environmental challenge of floating plastic and solid waste accumulation in natural water bodies. The proposed system integrates computer vision, embedded control, and IoT-based communication to enable autonomous detection, collection, and monitoring of water surface waste with minimal human intervention. By leveraging the YOLOv5 deep learning algorithm for real-time waste detection, the system significantly improves accuracy and operational efficiency compared to conventional manual and sensor-based cleaning methods.

The implementation of an embedded control architecture using an Arduino UNO microcontroller enables reliable coordination between the vision system, motor drivers, and conveyor-based waste collection mechanism. Experimental evaluation demonstrated that the system achieves high waste detection accuracy with low processing latency, allowing timely activation of the collection mechanism. The conveyor-based approach ensures continuous and efficient removal of floating waste, reducing the dependency on manual labor and improving operational safety. Additionally, the integration of IoT technology enables real-time monitoring of system performance and environmental parameters, supporting data-driven decision-making and effective supervision.

One of the key strengths of the proposed system lies in its cost-effective and modular design. The use of readily available hardware components makes the system economically feasible and scalable for deployment across various water bodies such as rivers, lakes, ponds, reservoirs, and canals. The autonomous nature of the system reduces manpower requirements and operational risks associated with polluted water environments, contributing to improved safety and sustainability. Furthermore, the system supports continuous operation and can assist municipal authorities and environmental agencies in identifying pollution-prone areas and maintaining water quality.

Despite its promising performance, certain limitations were identified during implementation and testing. The operational duration of the system is constrained by battery capacity, and detection accuracy may be affected by environmental factors such as lighting variations, water turbulence, and weather conditions. Additionally, onboard waste storage capacity limits long-duration deployment without maintenance. However, these limitations do not undermine the overall effectiveness of the proposed solution and can be addressed through future enhancements.

In conclusion, the proposed AI-driven IoT-enabled autonomous system provides a practical, efficient, and sustainable solution for water surface waste management. By combining intelligent waste detection, autonomous collection, and real-time monitoring, the system demonstrates strong potential for real-world implementation. With further improvements such as renewable energy integration, advanced navigation, and enhanced sensing capabilities, the proposed approach can play a significant role in mitigating water pollution and promoting environmental conservation.

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