

EcoX: An Autonomous IoT-Enabled Underwater Robot for Real-Time Microplastic Detection and Monitoring

Abstract—The tenacious rise in microplastic contamination across water bodies threatens aquatic ecosystem and human body. Traditional methods for monitoring such pollutions are often limited, sporadic and labor intensive, making them inadequate for timely and scalable environmental response. This proposed model will introduce an IoT-enabled underwater bot specially patented for autonomously detecting, monitoring and analyzing microplastic particles in real-time. The system integrates sensors such as turbidity sensor, optical particle sensor, pH sensor, Ultrasonic sensor, turbidity sensor, UV sensor and temperature sensors. The ESP32 serves as an edge device for real-time data processing. Data is transmitted through GSM or Wi-Fi protocols, secured with AES-256 encryption. This ensures seamless and secure communication between the local server and the system. The underwater robot autonomously performs action by detecting the presence of microplastic in different places in a river or pond. Users can control the robot using a remote control if the autonomous system faces any sensor malfunctions, navigation error or power depletion. The robot can then be safely guided to a predefined recovery point or instructed to resume operations after troubleshooting. The system is powered by a hybrid solution using solar energy and rechargeable batteries, promoting sustainability. By using Ubidots the data will visualize that are collected from the local server. The Robo-Driven architecture will offer sustainable, smart, autonomous and a cost-effective solution to monitor microplastic pollution. By combining sensor driven intelligence, autonomous navigation, secured communications and Realtime monitoring, this proposed model enables precise environmental assessment and proactive pollution mitigation.

Index Terms—Autonomous, Underwater Robotics, ESP32, Edge Computing, Smart Pollution.

I. INTRODUCTION

The increasing problem with microplastics in the water is becoming an environmental issue concerning threats to marine life and human health. Microplastics are plastic particles smaller than 5mm and are found nearly everywhere even in the water. The sources of these pollutants can be the breakdown of larger plastic materials or directly from the activities of humans. They can be found everywhere around the globe. Data sampling and laboratory analysis are ineffective to monitor microplastic pollution but require extensive manpower.

Moreover, they fail to provide adequate real-time data. As a result, these methods are not suitable to detect and manage such widespread contamination on time. The proposed system, as depicted in Fig. 1, combines various sensors like optical particle sensor, turbidity sensor, pH sensors, temperature sensors that are controlled by ESP32, which is an advanced edge computing device. This system is designed to work

autonomously. It collects data about microplastic particles in water bodies and communicates this information in real time.

Data transmission is secured through effective communication protocol while the energy requirements of the system are fulfilled using a hybrid solution consisting of solar cells and rechargeable batteries. The proposed model aims to provide a reliable, sustainable and efficient solution for monitoring the system of water bodies. By providing real-time assessment of the environment while allowing for timely detection of microplastic contamination, the system offers a unique approach to pollution management. The purpose of the research is to provide valuable information on how autonomous robotic systems can help in monitoring environments and in making better policies for safeguarding water bodies.

II. RELATED WORK

Monitoring systems for aquatic ecosystems must be developed to assess microplastic contamination. Conventional techniques involving manual sampling and laboratory analysis are often inefficient and labor-intensive. Recent studies have proposed autonomous IoT-enabled systems as viable alternatives. Prasad et al. developed a system for microplastic detection based on Raspberry Pi and convolutional neural networks (CNNs), but its generalizability was limited due to the dataset [1]. Ahmed et al. proposed a marine monitoring system integrating satellite communication, wireless sensor networks (WSNs), unmanned aerial vehicles (UAVs), marine sensor modules (MSMs) and autonomous underwater vehicles (AUVs); however, in remote oceanic environments, these systems may experience intermittent signal loss, delays or data gaps due to weather conditions or technical malfunctions, potentially hindering timely responses [2]. According to Abins et al., machine learning-based models such as YOLOv5 and Faster R-CNN have been reviewed for marine debris detection, but these systems faced challenges with turbidity and loss of materials [3]. Gopika and Nirmalrani demonstrated real-time detection using YOLOv8, though integration of debris removal remains an unresolved issue [4]. Sarker et al. utilized YOLOv5 and DeepSORT for real-time tracking of microplastics, encountering challenges related to water velocity and microplastic types [5]. Singh et al. reported that YOLOv8 provided the most accurate object detection among different YOLO versions [6]. Rajasekar and Geetha applied generative adversarial networks (GANs) to generate synthetic microplas-

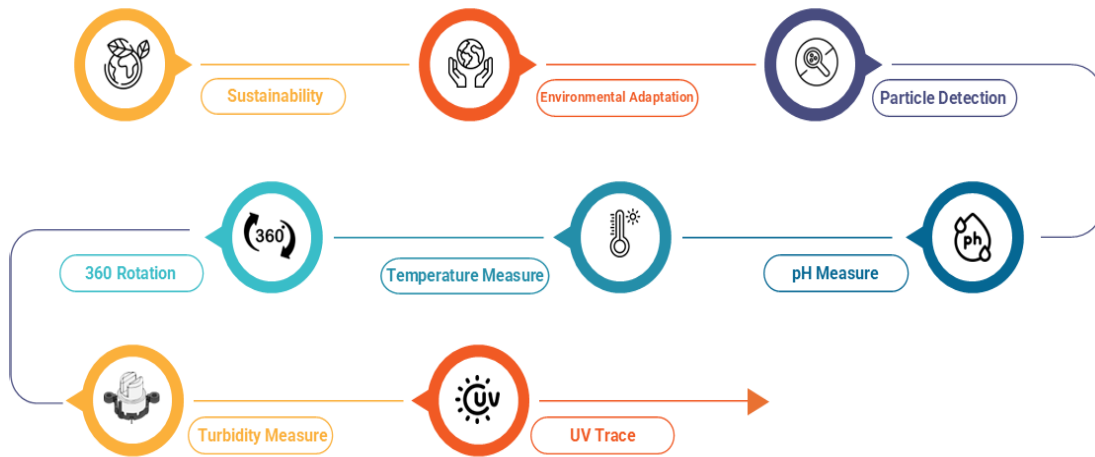


Fig. 1. Features of The Proposed Model

tic images, achieving 92.5% accuracy and helping to overcome dataset limitations [7].

Many studies have been performed on machine learning to detect microplastics, yet still face several limitations in autonomous vehicles and IoT-based platforms. Most of the current systems use either single-mode sensing or an image-based detection system which fails in highly turbid or low-visibility underwater conditions. There are a lot of platforms designed for the manual sampling and intermittent human intervention. Further, the infrastructural AUV- and UAV-based monitoring systems, presently, are not robustly secured for communication or efficient in operation with reliable fallback in sensor errors or navigation failures. There are hardly any studies that combine multi-sensor fusion with edge computing for real-time microplastic detection in water. More significantly, we are not aware of the existence of a low-cost autonomously navigating underwater robot system that runs on a hybrid combination of solar-battery power and secure internet of things (IoT) connectivity. Use your own words to write a paragraph on the need of a fully autonomous energy efficient securely connected underwater robot enabling real time microplastic detection through a multi-sensors data fusion. The AquaVeritas system is presented as a solution to these limitations. It combines the capabilities of an IoT-enabled underwater robot, multi-modal sensing (optical particle sensing, turbidity, UV, pH and temperature), AES-256 secured communication, ESP32-based edge processing, hybrid solar-battery power and manual override. This integrated approach provides a new, simple and effective solution for microplastic detection in water systems.

III. METHODOLOGY OF THE PROPOSED SYSTEM AND WORKFLOW

A. System Architecture of The Proposed Model

The proposed model of IoT-enabled autonomous underwater robot, as depicted in Fig. 2 is designed to provide real-time underwater environments monitoring with smart integration and local server base user interaction. The system utilizes smart sensors, high-end edge devices and GSM or Wi-Fi

based communication to ensure better communication even in adversarial conditions. The system architecture is divided into two parts. One is for Underwater communications and the other is for over the water communication.

1) *Underwater Bot*: The core of the robotics system is an edge device which is powered by a 12V,4Ah Lithium-Polymer (Li-Po) rechargeable battery. The edge device is used as slave mode [8]. This design makes the system more energy efficient and suitable for deep water exploration. An array of sensors including Optical Particle Sensor (OPS) to detect and count suspended microplastic particles based on light scattering, a Turbidity Sensor (TS) to measures water clarity which indicates the presence of particles including microplastics, a pH Sensor (PHS) to measure alkalinity of water, which may affect microplastic degradation, a Ultrasonic Sensor (US) to detects obstacles and measures distance underwater for navigation, a Temperature Sensor (TempS) to monitors water temperature to correlate with microplastic behavior, a Gyro Accelerator Sensor (GAS) to tracks orientation, acceleration, and movement stability during underwater navigation. A compass has been used to provide heading and directional data for accurate underwater path planning and control. The onboard camera captures images for microplastics detection. It processed the captured pictures using image processing and a lightweight AI model Tiny-YOLO to identify microplastics. The purpose of the sensors is to give accurate and more precise results. The Robo-Driven architecture will offer sustainable, smart, autonomous and a cost-effective solution to monitor microplastic pollution.

2) *Floating Device*: This master edge device is also powered by a 12V,4Ah Li-Po Battery and receives data from the underwater robot using a water resistance cable. Then, the AES-256 uses its own algorithm to encrypt the data, which employs a symmetric 256-bit key to convert readable sensor data into a secure ciphertext format, ensuring that sensitive information remains protected during transmission [9]. For lower energy consumption, the system prioritizes Wi-Fi for data transfer and sends it to the local server with GPS location.

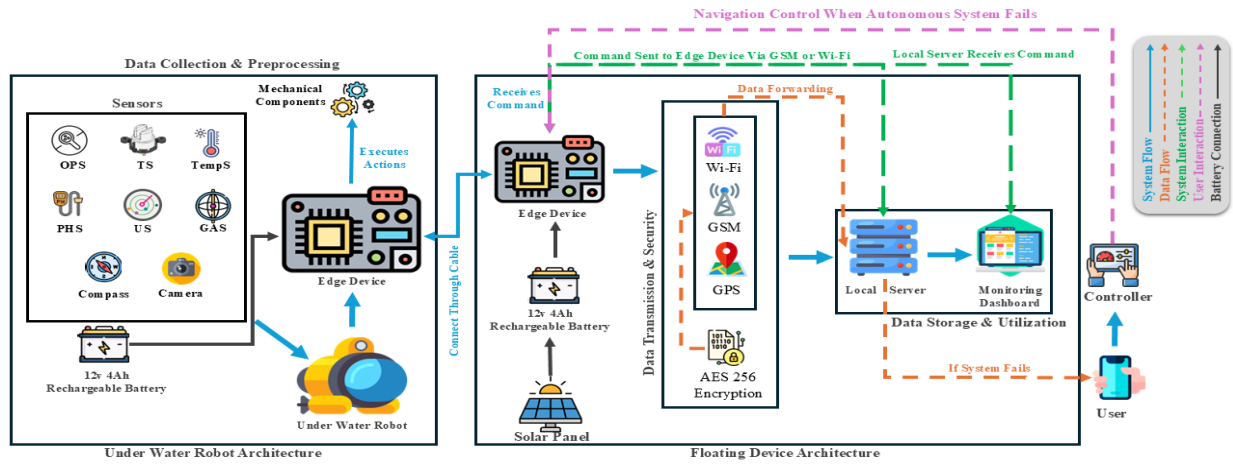


Fig. 2. System Architecture of The Proposed Model

The local server stores and processes the data, which may subsequently be accessed through Ubidots dashboard to view trends and receive alerts [1]. If Wi-Fi is not available, the system resorts to using a GSM module with an SIM card to maintain reliable local server connectivity [10]. Users can control the robot using a remote control if the autonomous system faces any sensor malfunctions, navigation error or power depletion. The robot can then be safely guided to a predefined recovery point or instructed to resume operations after troubleshooting. Notably, the underwater robot utilizes an edge device as a slave, while the floating device operates in master mode, ensuring robust coordination and control. This mechanism ensures high reliability and continuity in data collection. By combining sensor driven intelligence, autonomous navigation, secured communications and Realtime monitoring, this proposed model enables precise environmental assessment and proactive pollution mitigation. It is a promising step forward in aquatic ecosystem conservation and environmental data-driven policymaking.

B. Workflow of The Proposed System

The proposed model operates through a structured and adaptive workflow designed for efficiency and environmental responsiveness. The workflow, as depicted in Fig. 3, starts with the initialization of the system where all components including sensors, edge devices, communication devices go through a diagnostic checkup to ensure robust functionality. Then the sensor collects data and the camera captures images. After collecting data from the underwater environment, it proceeds to the data processing stage.

This data is locally processed on the underwater ESP32 edge device, where collected data is checked for quality and raw images are pre-processed for microplastic detection. The processed data is then sent to the floating device. Using AES-256 encryption, it is securely transmitted to the local server. The server receives, stores, and further processes the encrypted data. It is visualized on the Ubidots dashboard, showing trends, alerts and real-time monitoring. Data transmission occurs via

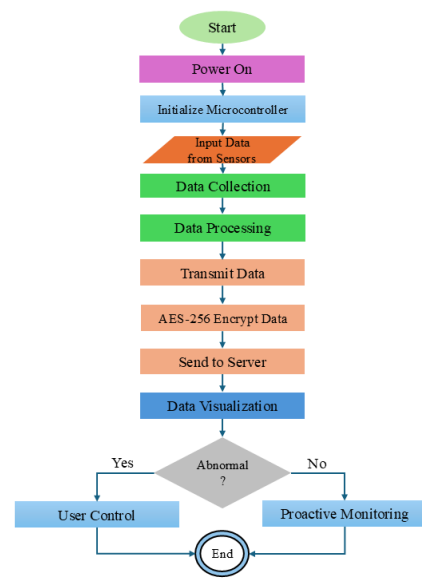


Fig. 3. Workflow of The Proposed Model

Wi-Fi or GSM (if Wi-Fi is unavailable). If abnormalities are detected, the user can manually control the device for a safe exit. The system also detects anomalies in real-time such as excessive microplastics or abnormal sensor readings and triggers proactive responses or alerts. When necessary, it can be directed to a pre-defined recovery point or restarted after fault detection. The robot continues to collect and send data until the battery is depleted. Once the mission is complete, it can return home to recharge or continue monitoring.

C. Simulated Hardware Implementation of The Proposed Model

The hardware simulation of the proposed system, as depicted in Fig. 4, integrates various components to ensure efficient and reliable operation. The slave ESP32 microcontroller serves as the core processing unit, handling data from sensors and executing commands and sending to the master ESP32 mi-

crocontroller. The GSM module ensures data communication in areas without Wi-Fi. The power system, comprising solar panels and rechargeable DC batteries, provides a sustainable energy source, ensuring uninterrupted operation under various conditions. This cohesive integration of hardware components ensures the system’s functionality, scalability, and adaptability for underwater microplastic detection. Moreover, the inclusion of camera module, optical, turbidity, temperature, pH, ultrasonic, compass and gyro accelerator sensor allow the system to respond dynamically to environmental changes, offering automated adjustments in real time. Each hardware module is programmed to communicate over a unified control bus, improving synchronisation and reducing latency.

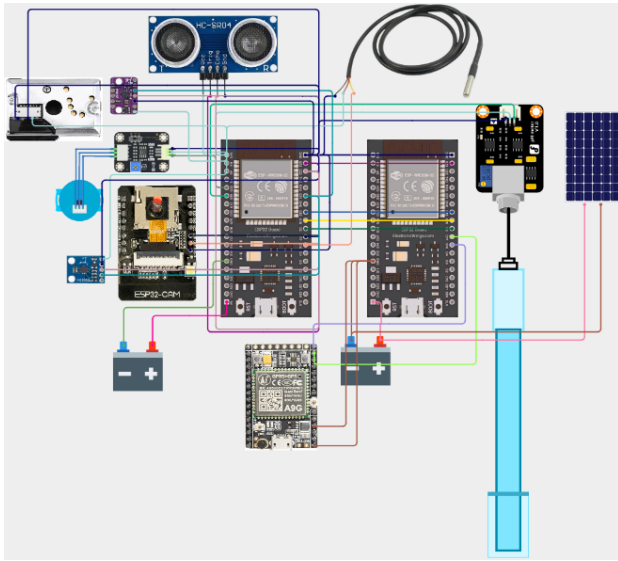


Fig. 4. Hardware Implementation of The Proposed Model

IV. CASE STUDY AND DISCUSSION

Global concern is growing owing to increasing contamination of water bodies with microplastics. Conventional monitoring techniques for these contaminants are constrained because of their dependence on human action, intermittent sampling, and irresponsibility. The traditional way of working in environmental management is slow to identify and resolve problems. The use of autonomous systems augmented with IoT technologies offers one solution to continuously monitor and combat microplastics in water bodies.

A. Proposed Solution

The IoT-enabled autonomous underwater robot proposed for the present study works and solves a major problem of traditional methods for detecting microplastics. The robot equipped with optical particle sensors (OPS), turbidity sensors (TS), depth sensors (DS) etc. can detect microplastic particles in real-time. The system utilizes a solar energy-hybrid rechargeable battery which produces 100% natural output power and provides seamless operation.

B. Key Insights of The Proposed Model

1) *Real-Time Monitoring:* The system provides real-time monitoring of water bodies, whereby it is able to identify microplastics and other parameters, including temperature, pH and turbidity. This enables environmental agencies to take swift action based on the data collected, rather than waiting for delayed reports.

2) *Autonomous Operation:* The robot operates autonomously, with the ability to navigate and collect data without human intervention. If there are problems with the sensors or navigation, the robot can be manually controlled through a remote if required, so it can be safely brought back to a safe point.

3) *Energy Efficiency and Sustainability:* The system is based on solar panels and battery charging. Hence, it greatly reduces the environmental footprint of conventional, power-hungry monitoring systems. The solar energy solution makes it easier to transport to remote or off-grid locations, creating more sustainable operations.

4) *Data Security:* The encryption of the data from the robot to other devices uses AES-256 so that the environmental data can be protected while being transmitted. This feature is important to maintain the integrity of the data, especially when the data goes to research institutions or governments.

C. Cost Analysis

A detailed cost analysis shown in Tab. I compares component expenses and installation costs against potential energy savings. Initial deployment costs are higher, but this investment is offset by significant long-term economic and environmental benefits. The modularity of the design allows for easy maintenance and future scalability, reducing future costs and enhancing the system’s longevity and return on investment.

TABLE I
ESTIMATED COST OF COMPONENTS

Components	Units	Estimated Cost (USD)
ESP32 Microcontroller	2	\$8.00
Optical Particle Sensor	1	\$10.80
Turbidity Sensor	1	\$11.70
pH Sensor	1	\$20.80
Ultrasonic Sensor	1	\$4.90
Temperature Sensor	1	\$8.30
Gyro Accelerator Sensor	1	\$2.10
Compass Sensor	1	\$3.20
Camera Module	1	\$7.40
Solar Panel (35W)	1	\$16.70
Rechargeable Battery (12V, 4Ah)	2	\$65.00
GSM + GPS Module	1	\$22.10
Thruster Motors	4	\$210.00
Wire (50m)	1	\$10.00
Mounting Accessories & Case	1	\$30.00
Total Estimated Cost		\$431.00

V. RESULTS AND ANALYSIS

The findings of the simulated hardware implementation of the proposed IoT-enabled underwater robot for microplastic detection is presented in this section. The results were gathered

TABLE II
SENSOR DATA LOG

sno.	latitude	longitude	depth (m)	temp (°C)	pH	turb (NTU)	op count	cam count	YOLO conf	micro (mg/L)	Batt (%)	latency (ms)
1	23.7807870	90.2793500	2.9	24.72	7.57	1.17	22	17	0.843	0.0043	99.20	37
2	23.7809298	90.2793082	2.39	24.92	7.58	1.34	62	46	0.909	0.0023	98.14	48
3	23.7810741	90.2794465	2.31	24.99	7.48	1.75	91	59	0.688	0.014	97.47	56
4	23.7811057	90.2789001	3.02	24.94	7.60	1.93	115	72	0.880	0.0043	96.83	59
5	23.7808654	90.2790504	3.72	24.86	7.60	1.94	117	77	0.990	0.0021	95.79	61

through a hardware model using an ESP32 that is integrated with a number of sensors. Data visualization consists of simulated readings of turbidity, optical particle count and overall data correlation.

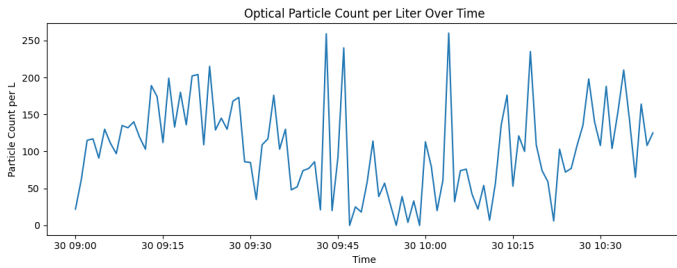


Fig. 5. Optical Particle Count

The optical particle count taken during simulation period is shown in Fig. 5. The data indicate that the concentration of particles ranges between 0 and 250 (particles/L). This shows the amount of suspended microplastic particles vary over the sampling period. The above figure indicates high microplastic density in the peak areas and low microplastic density in the low areas. In other words, an optical particle sensor can detect the change in water quality at real-time due to the response and sensitivity.

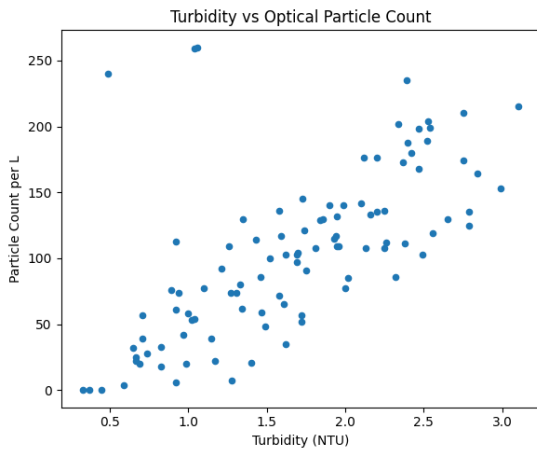


Fig. 6. Turbidity vs Optical Particle Count

Fig. 6 shows how turbidity and optical particle number are related. There is a positive correlation in the plot higher

turbidity levels correspond to higher optical particle counts. This finding shows that turbidity can be a supporting factor for particulate matter, including microplastics. But turbidity will not differentiate between organic or inorganic particles so we can combine turbidity with optical detection. The correlation coefficient obtained ($r = 0.68$) confirms turbidity as a reliable parameter for microplastic prediction.

Tab. II summarises the combined data reading from a temperature, pH, turbidity and optical particle counters as readings from other sensors. The temperature did not vary much, as it remained stable between 24.72–24.99°C, while pH was between 7.48–7.60 at the points sampled. According to the findings, an increase in the turbidity from 1.17 NTU to 1.94 NTU occurred. It was in accordance with the rise in the optical particle counts (22 to 117). This confirms the previously established correlation that turbidity has a positive relationship with suspended particle density. The detection confidence of the Tiny-YOLO camera module was recorded in the range 0.688 to 0.990. The lower confidence at Test 3 could be due to 1.75 NTU higher turbidity level. The concentration of the derived microplastic from all test points ranged between 0.0021 mg/L to 0.014 mg/L indicating that even low-density microplastic can be detected with good sensitivity. The charge levels of the battery during the five test batteries gradually decreased from 99.20% to 95.79%. Thus, it shows good charging efficiency of the ESP32 and other sensors and communication batteries. Latencies measured between 37 ms to 61 ms which shows stable real-time data transmission over the network with minimal delays This shows that the communication architecture can allow for constant monitoring without losing much data or lagging.

The overall results indicate that the proposed IoT-enabled underwater robot can identify and quantify the microplastics, while keeping the communication performance stable and using energy efficiently. The continuous sensor readings and reliable YOLO-based visual detection, along with stable power levels and low transmission latency, show that the system is scalable and robust for real-time microplastic monitoring on aquatics.

VI. CONCLUSION AND FUTURE WORKS

The autonomous underwater robot in IoT presented in this research can offer a possible solution to the issue of microplastics in water. The integration of several sensors via the ESP32 for edge computing can detect and monitor

microplastics in real-time. The solar battery-powered hybrid solution ensures your remote or off-grid application operates always by recharging the battery with solar energy. The system works autonomously and securely transmits data in real-time after the AES-256 encryption of evaluated data to report accurately. By utilizing this method, monitoring can be conducted effectively while also preventing pollution. The autonomous motion for data collection which has a manual control for necessary help makes the system reliable and robust in nature. Ultimately, this scheme is a significant step for environmental monitoring. It can also offer a scalable, sustainable and affordable solution to microplastic pollution. The future can improve sensor accuracy, communication technologies, and multi-robot coordination. This can increase the capability and applicability of the systems. Thus, contributing to effective conservation and policymaking.

Future developments should aim to enhance sensor robustness, adopt alternative communication methods such as satellites or LPWAN, and integrate AI for improved navigation and obstacle avoidance. Additionally, optimizing energy usage, enabling multi-robot coordination, and connecting the system to broader environmental monitoring networks can significantly improve its effectiveness and support conservation initiatives.

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