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Particle Swarm Optimization Based Efficient Path Planning in Autonomous Marine Trash Collection

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ABSTRACT

This research introduces an innovative solution to marine pollution through the development of a Marine Trash Collector optimized using Particle Swarm Optimization (PSO). Inspired by the collective behavior of bird flocks moving toward areas with abundant food, PSO enables the robot to determine the most efficient path for cleaning water bodies by treating each possible route as a "particle" and optimizing it to minimize time and energy while maximizing trash collection. The robot, powered by an Arduino and guided by a GPS system, uses a conveyor-based mechanism and real-time sensor input to adapt to varying water conditions. When tested, the PSO-optimized model performed better than manual and semi-autonomous modes, collecting more trash in less time and with lower energy consumption. Overall, the system demonstrates strong potential as a scalable, energy-efficient, and intelligent solution for marine waste management, contributing meaningfully to global efforts for cleaner and healthier oceans.

Keywords: PSO,GPS based navigation, Swarm Intelligence, Waste Management, Robotics, Automation, IoT, Environmental Issues, Sustainable Development

INTRODUCTION

Marine pollution, especially plastic waste, is one of the biggest environmental challenges today. Every year, millions of tons of plastic waste enter our oceans, which harms marine life and disrupts ecosystems. Traditional methods of cleaning polluted water bodies are often inefficient, slow, and expensive, making it difficult to tackle this growing problem. The below diagram illustrates the trash density along different state coastlines in the United States.

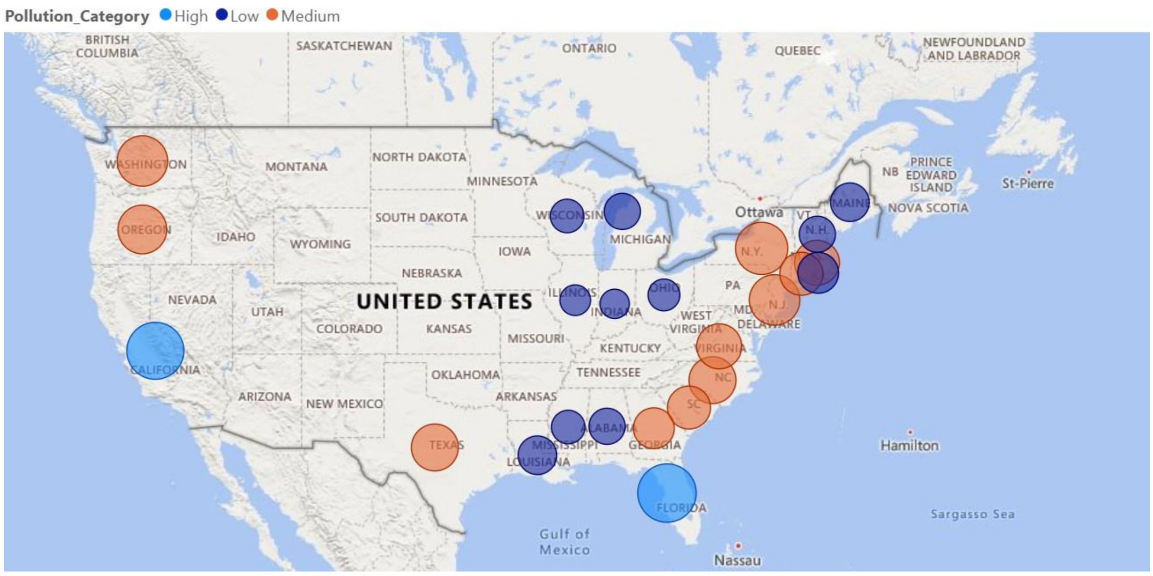

Fig 1: Trash Density along coasts of U.S.

To address this, the aim of this project is to develop an autonomous Marine Trash Collector that uses an optimization algorithm called PSO (PSO) to find the most efficient path for collecting waste from water bodies. The main objective of this project is to create a robot that can collect trash in the shortest time, with the least energy and effort and optimized to greatest efficiency levels for least power wastage. PSO is a nature-inspired algorithm, it uses an example from nature: based on how groups of animals, like birds or fish, work together to find food. In this system, the robot continuously adjusts its path in real-time to find the most efficient route for cleaning the water. The Marine Trash Collector is powered by a Raspberry Pi 3B+, which works in coordination with GPS sensors and PSO algorithms written in Python to collect and process data. This data is then transmitted to an Arduino Uno microcontroller that controls the robot's movement and navigation. The system uses a conveyor belt mechanism synchronized with trash density measurements to reduce energy wastage and improve the accuracy and efficiency of automatic trash collection. The significance of this research lies in its potential to offer a sustainable, efficient way to clean oceans and rivers. By using PSO, the robot can adapt its route based on real-time data, ensuring it collects the maximum amount of waste in the least time, while using minimal energy. This system could be scaled and used in different locations around the world to help reduce plastic pollution and improve the health of our water bodies. This approach not only contributes to the healthier aquatic ecosystems, but also provides a way for future innovations in environmental robotics and intelligent waste management technologies. To increase the visibility and encourage community engagement, this project has been presented under the name **Nauticlean** with a supporting website which shares its purpose and design [1].

LITERATURE REVIEW

The accumulation of marine waste—particularly plastics and microplastics—is a growing environmental crisis with wide-ranging impacts on marine ecosystems, biodiversity, and human livelihoods. According to the International Union for Conservation of Nature (IUCN), over 11 million metric tons of plastic waste enters the oceans every year, a figure projected to triple by 2040, if no substantial interventions are made. Microplastics, which are small plastic fragments resulting from the breakdown of larger debris, have been found in fish, sea salt, and even drinking water, raising significant health concerns. Marine waste obstructs natural water flow, poses ingestion and entanglement hazards to marine life, and disrupts the beauty and usability of coastal areas. Conventional methods of waste collection are labor-intensive, limited in reach, and ineffective at addressing the scale and complexity of the issue.

Several technological solutions have been developed to address this growing concern. The WasteShark, developed by RanMarine [2], is a surface robot that moves across water and collects floating waste using a simple container-based system. However, it requires manual unloading and cannot function for long durations without human help, making it less efficient for continuous operations.

The Intelligent Water Surface Cleaner Robot (IWSCR) presented by Arora and Jain [3] is designed to move on water and collect garbage using a basic mechanical structure.

Though it automates collection to some extent, it lacks advanced navigation and results in higher energy consumption and limited coverage.

The Ocean Cleanup's Interceptor [4] was created to stop plastic waste from entering oceans through rivers. It works by collecting trash near river mouths and directing it into a storage bin. While effective in ideal conditions, the Interceptor has suffered damage during floods and heavy rains, raising concerns about its durability in extreme weather.

The SeaClear Project [5] introduces an underwater robotic system to detect and remove garbage from the seabed. It uses coordinated robots for locating, identifying, and collecting trash. However, the system struggles with detecting waste in murky or complex underwater environments and is still under testing for wide-scale use.

Liang et al. [6] developed a robot that uses spiral movement to gather trash spread over large surface areas. Although this movement improves coverage, it may not be efficient in areas with scattered or uneven trash distribution.

Wang et al. [7] used a particle-based optimization method to plan the movement of garbage-collecting robots. This technique helps improve efficiency in route planning, but it still depends heavily on accurate sensor data and controlled conditions to perform well.

Bhosale and Patil [11] introduced a solar-powered river cleaning robot aimed at reducing pollution in flowing water. It promotes sustainability, but solar efficiency drops in cloudy weather or during nighttime, reducing its reliability.

Singh and Kaur [12] designed a conveyor-based robot to collect trash from ponds and lakes. The model provides a good mechanical solution, but its bulkiness and lack of autonomous control limit its use in larger or more dynamic environments.

Compared to these existing systems, the proposed marine trash collector improves on multiple fronts. It combines smart GPS navigation to follow an optimized cleaning path and uses a fin-based propulsion system that works well even in narrow or cluttered water bodies. Unlike models that require manual unloading, this prototype is able to dock and unload trash automatically. Its structure is more compact and energy-efficient, making it more suitable for long-term use. Overall, the model offers a more reliable, adaptable, and cost-effective solution for addressing water pollution caused by floating waste.

METHODOLOGY

The prototype designed is constructed on a durable, lightweight Sunboard base, chosen for its waterproof and floatable properties, ensuring stability while operating in water bodies. The system uses Arduino Uno as the primary controller and a Raspberry Pi 3B+ for processing and decision-making tasks. A GPS module is used for real-time location tracking, while DC motors enable movement across the water surface. The trash collection mechanism is powered by a conveyor belt that adapts to different directions based on trash concentration. Sensors are installed to detect the presence of waste and guide the system accordingly. The basic flow diagram of the designed model is shown in Fig. 2.

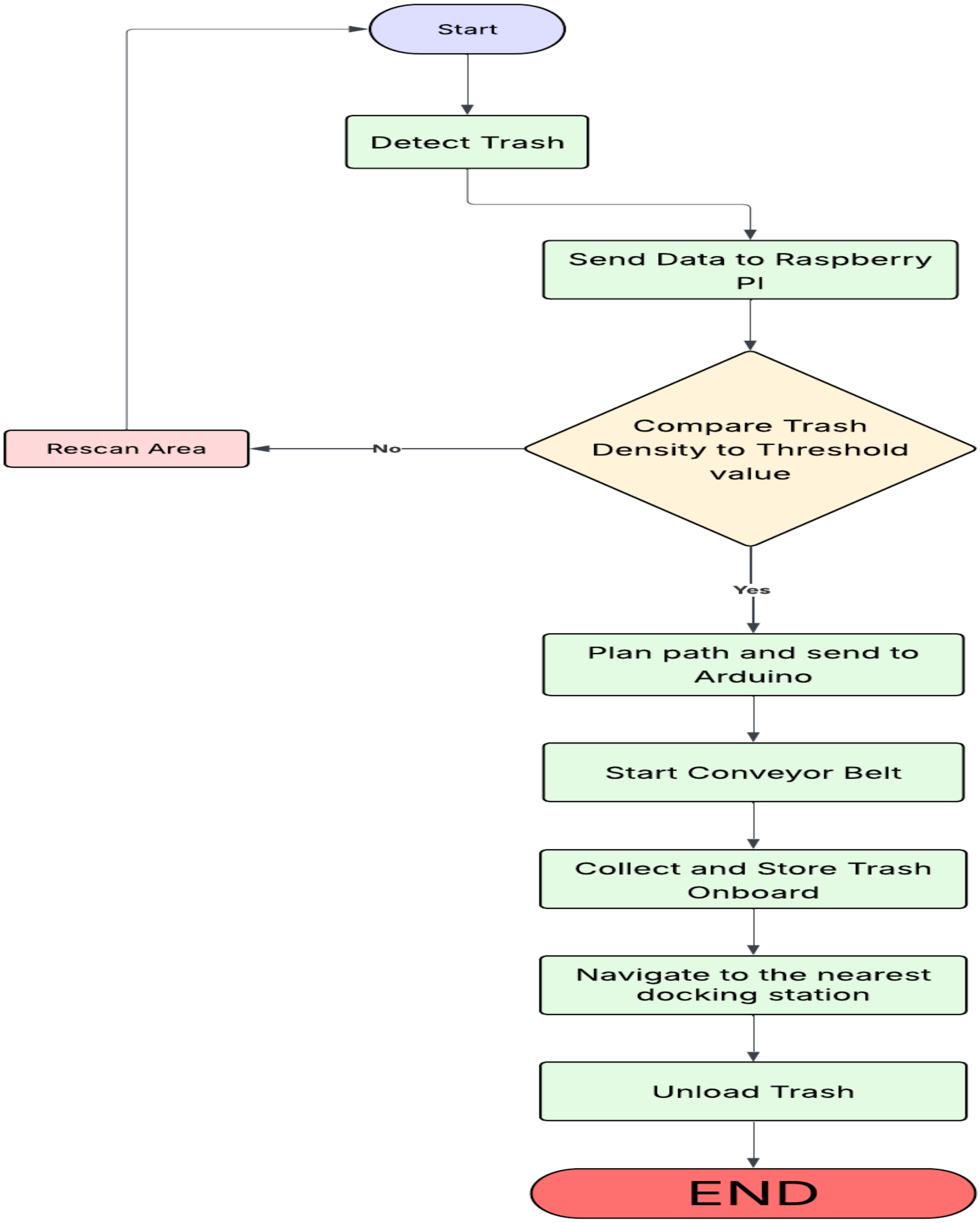

Fig 2: Flowchart of Marine Trash Collector

The flow chart outlines the complete operational cycle of the model. If trash density is low, the system either waits or re-scans the area. When cleaning is initiated, the onboard conveyor belt starts collecting trash efficiently as the model moves along the optimized route. Once the trash is collected, the system returns to the docking station and transfers the waste to a processing unit. The conveyor adjusts its motion based on the trash spread, enhancing coverage and ensuring efficient collection. This integrated and automated approach reduces human involvement and provides a scalable, cost-effective solution for cleaning polluted water bodies.

PSO

PSO is a method used to find the best solution to a problem by simulating the way birds fly in a group or fish swim in schools. In this technique, each possible solution is treated like a "particle" that moves around in the search area. These particles keep track of two things: the best solution they have found so far (called personal best or *pBest*) and the best solution found by any particle in the group (called global best or *gBest*). Using this information, each particle changes its direction and speed in the hope of getting closer to the best possible solution. Over time, the particles move towards the area where the best answer is likely to be found. PSO is helpful in solving real-world problems where we need to find the most efficient or optimal result.

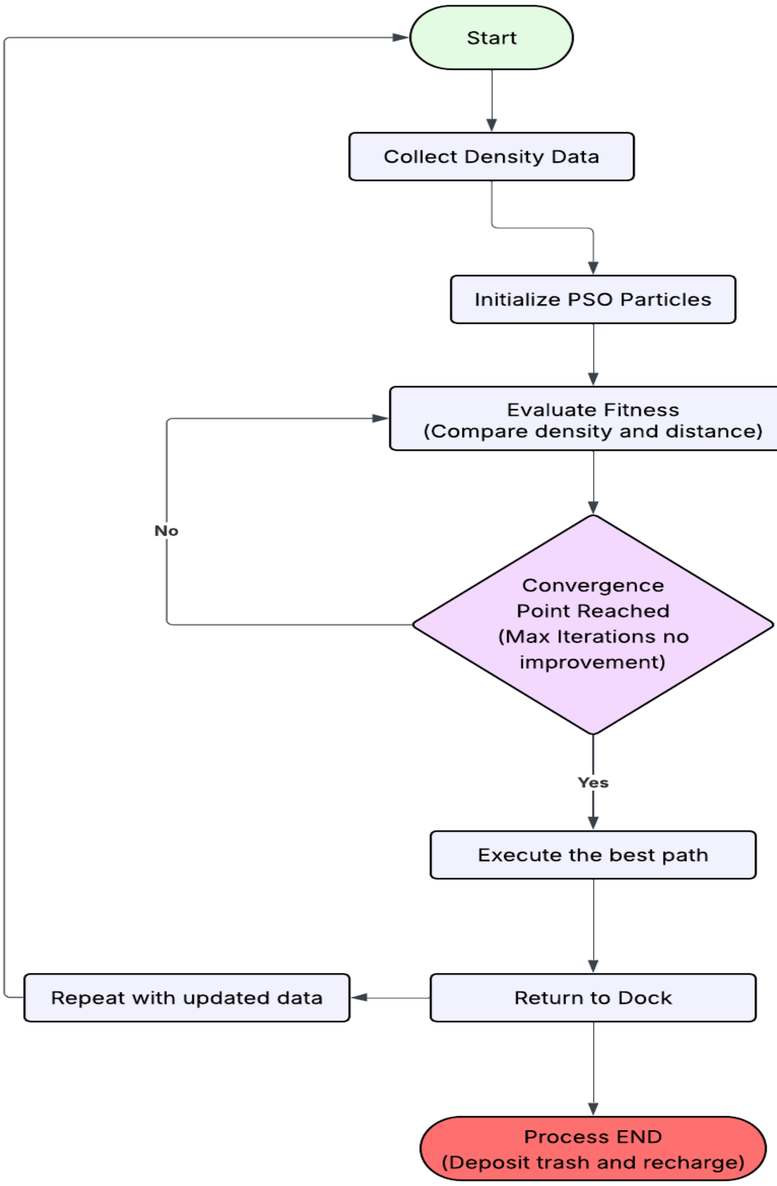

Fig 3: Flowchart of PSO in the proposed model

The proposed marine trash collector uses PSO (PSO) to plan the most efficient path for collecting trash. PSO is a smart algorithm that works like a group of birds searching for food—it helps the system decide which areas have the most trash and how to reach them quickly. Using GPS data and trash density inputs, the model calculates the best route to clean high-trash zones while avoiding unnecessary movement. This helps the system save time and energy, making it more effective and efficient in cleaning polluted water bodies.

RESULTS AND OBSERVATIONS

The performance of the model was evaluated across three operational modes: manual collection, semi-autonomous collection, and semi-autonomous collection optimized using PSO (PSO). Key metrics considered include collection time, energy consumption, trash collected, accuracy, and manpower requirements.

Table 1: Comparative Performance Analysis of Trash Collection Methods

Collection Type	Time (in hours)	Energy (in kWh)	Trash Collected (In Grams)	Accuracy (In Percent)	Manpower required
Manual	2.64	0.69	431.2	65	5
Semi-Autonomous	2.37	0.67	467	92	1 (supervisory)
Semi-Autonomous with PSO	1.98	0.51	609	95	1 (supervisory)

Impact of PSO on system efficiency

When PSO (PSO) was added to the semi-autonomous trash collector, the system became faster, smarter, and more efficient. Compared to manual and semi-autonomous models, it showed clear improvements in speed, energy use, and trash collection. PSO enabled intelligent path planning based on trash density, reducing human supervision while maintaining high accuracy. Figure 4 shows the comparison of all three collection methods across key efficiency metrics, highlighting the performance gains achieved with PSO integration.

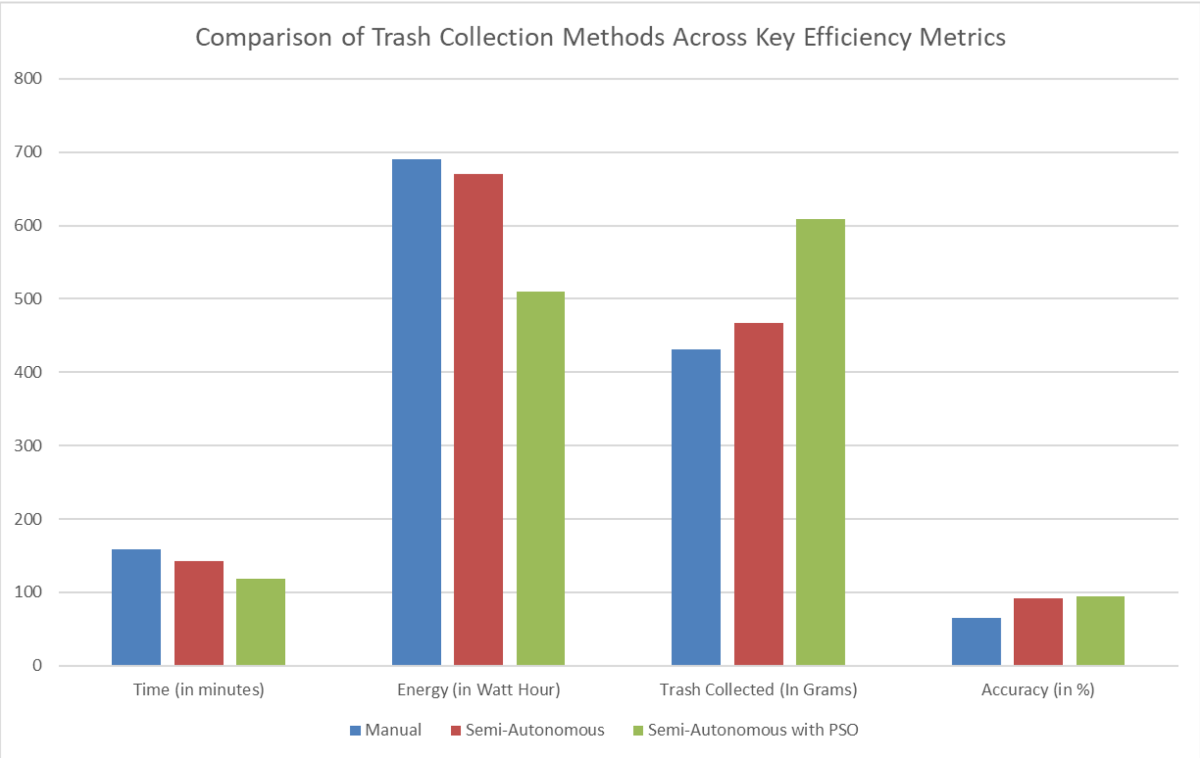

Fig 4: Comparison of Trash Collection Methods Across Key Efficiency Metrics

The integration of PSO (PSO) significantly enhanced the performance of the semi-autonomous marine trash collector. Cleaning time per 1000 m² decreased from 158.4 minutes in manual operation to 118.8 minutes with PSO, representing a notable improvement in efficiency. Energy consumption was reduced from 690 Wh to 510 Wh, while the amount of trash collected increased from 431.2 g to 609 g. Accuracy in trash detection and collection also improved markedly, from 65% in manual operation to 95% with PSO. Additionally, manpower requirements dropped from five operators to a single supervisor, highlighting both labor and operational efficiency. These results demonstrate that PSO effectively optimizes cleaning routes and system performance, enhancing speed, accuracy, and resource utilization.

From these results, it is clear that PSO helped reduce both time and energy, while also improving accuracy and the amount of trash collected. This shows that optimization can make a big difference in real-world cleaning systems and can be very useful if applied on a larger scale in lakes, rivers, and oceans.

DISCUSSION AND ANALYSIS

The evaluation clearly shows the benefits of automation and PSO optimization in marine trash collection. Manual operation required 2.64 hours per 1000 m², consumed 0.69 kWh, and collected 431.2 g of waste at 65% accuracy, while involving five personnel. The semi-autonomous system improved efficiency, reducing collection time to 2.37 hours, energy use to 0.67 kWh, and increasing accuracy to 92%, with only one operator needed. Incorporating PSO optimization further enhanced performance, achieving 1.98 hours, 0.51 kWh, 609 g of waste, and 95% accuracy. These results highlight faster, more energy-efficient, and labor-saving operations.

Existing marine cleaning robots offer useful functions but have limitations. WasteShark [2] and IWSCR [3] automate collection but require manual unloading and lack optimized navigation. The Interceptor [4] works well at river mouths, but is vulnerable to floods, while SeaClear [5] struggles in murky underwater conditions. Spiral-motion [6] and PSO-based path planners [7] improve coverage but depend on controlled environments and precise sensor data. Solar-powered [11] and conveyor-based

[12] systems address energy and mechanical collection but face weather dependency or bulkiness. In contrast, the proposed PSO-optimized collector combines autonomous GPS navigation, fin-based propulsion, automated docking, and energy efficiency, achieving higher collection efficiency, reduced time, and minimal manpower.

Limitations remain, including testing in controlled conditions, PSO's sensitivity to parameter tuning, and absence of sensors for microplastic detection or waste classification. Overcoming these challenges is crucial for deploying the system in rivers, lakes, and marine environments.

CONCLUSION AND FUTURE SCOPE

This study presents the design and development of a semi-automated marine trash collector capable of detecting and retrieving floating waste using GPS-assisted navigation. The system introduces several improvements over conventional models, including energy-efficient operation, adaptive routing based on trash density, and an unloading mechanism at a designated docking station. These features enhance the system's practicality for addressing water pollution. During prototyping, key challenges included integrating GPS with the microcontroller, developing an effective fin-based propulsion mechanism, and maintaining optimal weight distribution of the floating platform. Despite these constraints, the prototype demonstrated promising performance under controlled conditions.

Future work will focus on advancing the system toward full autonomy through the integration of enhanced sensors for diverse waste detection, including microplastics. The incorporation of AI-based image recognition could enable real-time classification of biodegradable and non-biodegradable waste, while solar energy integration would improve sustainability. Further research should also prioritize compactness, cost-effectiveness, and large-scale adaptability, supported by collaborations with environmental organizations and governmental agencies for real-world validation.

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