Intelligent Beach Cleaning Robot

Yathunanthanasarma B.
Department of Electrical Engineering
University of Moratuwa
Colombo, Sri Lanka.
yathunanthanasarmab.19@uom.lk

Barathraj M.
Department of Electrical Engineering
University of Moratuwa
Colombo, Sri Lanka.
barathrajm.19@uom.lk

Mahiliny J.
Department of Electrical Engineering
University of Moratuwa
Colombo, Sri Lanka.
mahilinyj.19@uom.lk

A. G. B. P. Jayasekara
Department of Electrical Engineering
University of Moratuwa
Colombo, Sri Lanka.
buddhikaj@uom.lk

***Abstract* - Coastal pollution, driven by the accumulation of plastics and debris on beaches, presents a severe threat to natural habitats and marine ecosystems. Manual cleaning efforts, while valiant, are labor-intensive and insufficient to address the scale of the problem. Intelligent beach cleaning robots offer a promising solution by integrating advanced technology with environmental stewardship. This paper reviews existing robotic refuse collection mechanisms and introduces an Intelligent Beach Cleaning Robot equipped with dual modes of refuse collection mechanisms (raking and sieving shaker), object detection, autonomous navigation, and obstacle avoidance systems. Through rigorous testing and analysis, we achieved an accuracy of 93% in plastic debris detection using the YOLOv5 model. The robot's raking mechanism effectively collects debris within a 6-second timeframe, while the sieving shaker mechanism operates at an optimal frequency of 2.5 Hz for efficient sand filtration. The proposed prototype aims to enhance the refuse collection capabilities in a cost-effective manner, addressing the critical need for adaptable and efficient beach cleaning solutions.**

***Keywords - Beach Cleaning Robot, refuse collection, rake, sieving shaker, object detection, YOLO v5, autonomous navigation, predefined path, obstacle avoidance, fuzzy logic*.**

I. INTRODUCTION

Coastal pollution, aggravated by the accumulation of plastics and debris on beaches, poses a significant threat to our natural habitats and marine ecosystems. Alarmingly, an estimated 8 billion tonnes of plastics enter our beaches each year, underscoring the urgency of the issue. These pollutants not only endanger marine life but also exacerbate environmental challenges, creating a pressing need for effective intervention measures.

Historically, manual beach cleaning efforts have been employed as valorous attempts to mitigate coastal pollution. However, these methods are labor-intensive, time-consuming, and can lead to health issues for workers, including musculoskeletal diseases. Moreover, given the vast scale of the problem, relying solely on human labor proves inadequate.

The limitations of manual cleaning efforts highlight the necessity for advanced technological solutions capable of supplementing and enhancing human interventions. Addressing these challenges demands an automated, sustainable, and efficient approach to beach cleaning.

This paper advocates for the deployment of intelligent beach cleaning robots as a promising solution towards a more sustainable and efficient strategy for combating coastal pollution. By integrating cutting-edge technology with environmental regulations, these robots aim to safeguard our beaches and marine ecosystems while reducing the burden on human labor.

This paper begins with a literature review to contextualize the research landscape, followed by a detailed description of our system overview and design methodology. We then present our findings and discuss the results, leading into our future work and concluding remarks.

II. LITERATURE REVIEW

The development of robotic refuse collection mechanisms has emerged as a critical area of research in recent years, addressing the pressing need for efficient waste management in coastal areas. Various robotic systems have been introduced, each with unique design approaches and functionalities aimed at tackling the challenges of beach cleaning.

One notable system, the "Binman," [1] employs a filtration component with a conveyor equipped with steel tines exhibiting spring-like characteristics. While effective in waste capture, its continuously rotating conveyor belt results in inefficient energy usage and high battery consumption. Another system, "Hirottaro," [2] utilizes a brush mechanism inspired by human floor cleaning, achieved through a linkage mechanism. However, this design is characterized by its substantial size and associated costs. Modular robots have also been explored, with one design featuring an anterior claw appendage [3] for can retrieval. Despite its adaptability, this gripper design demands a significant power supply. Other approaches include radio-controlled bots [4] with sieve-like filtration and specialized picking-up mechanisms, though these are often limited in their waste collection capabilities.

In terms of waste identification and navigation, some robots have incorporated deep learning neural networks [5] and ultrasonic sensors [6], while others have employed autonomous navigation frameworks utilizing LiDAR or scanning range finders [2]. These technological integrations highlight the advancements in object detection and navigation capabilities within the field. While each robotic design presents unique advantages, they also exhibit significant drawbacks such as energy inefficiency, size, expenses, and limitations in waste collection capabilities. A critical gap identified from prior research is the need for robust collection systems capable of adapting to varying types and sizes of debris commonly found on beaches.

In response to the challenges and insights gathered from prior research, this paper introduces an Intelligent Beach Cleaning Robot designed to address the limitations observed in existing robotic beach cleaning systems. By leveraging intelligent systems and innovative design approaches, this research aims to enhance refuse collection capabilities in a cost-effective manner. Here, we introduce dual-mode approach namely raking mechanism and sieving shaker mechanism which underscores the importance of distinct mechanisms for plastic collection and sand filtration respectively by emphasizing adaptability to varying types and sizes of debris commonly found on beaches. Building upon previous work, this cost-effective solution seeks to contribute significantly to the advancement of robotic beach cleaning technologies.

III. System Overview

The integrated refuse collection system, depicted in Fig. 1, embodies a comprehensive approach to modern waste management, combining innovative technologies to enhance efficiency and efficacy. The collaborative operation of raking and sieving shaker mechanisms optimizes refuse collection. Advanced object detection, facilitated by YOLO-based algorithms, ensures precise identification and classification of target materials, enabling swift and accurate collection processes. Autonomous navigation capabilities enable seamless movement across diverse terrains, while obstacle avoidance algorithms ensure safe traversal in dynamic environments. Furthermore, the integration of predefined path following algorithms enables optimized route planning, thereby enhancing operational efficiency and minimizing resource consumption.

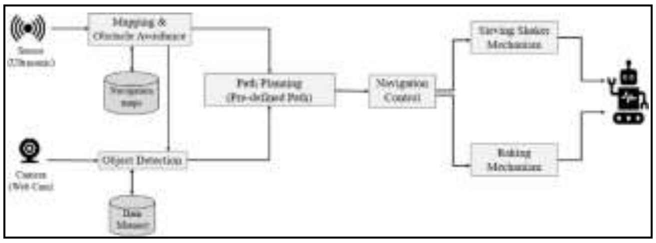

Fig. 1 System Overview

IV. Materials and Methods

The proposed prototype combines the two modes of refuse collection mechanisms to be affixed onto a tracked mobile robot platform. The mechanisms of modes were designed using SolidWorks software *(Fig. 2, Fig. 3)* and fabricated using stainless steel material *(Fig. 4, Fig. 5).*

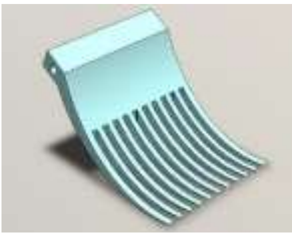

Fig. 2 Design of Rake

Fig. 3 Design of Sieving Shaker

Fig. 4 Fabricated Rake

Fig. 5 Fabricated Sieving shaker.

A. Raking Mechanism

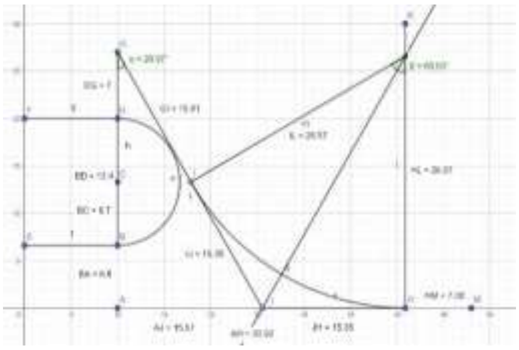

Fig. 6 Rake Design by Geometric Tool

The raking mechanism *(Fig. 4)* is designed with a rake-like implement featuring a revolute joint arm with one degree of freedom (1-DOF), facilitating the elevation of debris into a designated storage bin. The dimensions of the rake are 32 cm in width and 25 cm in length, with a height of 20.4 cm from the ground level. Each branch of the rake incorporates a 30:31 dual curve bending and maintains a spacing of 1.6 cm within the array. Components for this mechanism are fabricated using stainless steel material.

As shown in Fig. 6, the design parameters of the raking mechanism are optimized for lifting surface-level debris, delineating linear and bending areas based on design requirements. The rake is fabricated from stainless steel, weighing approximately 1 kg. The dimensions of the key areas are as follows: Top Linear Area $\approx$ 16 cm, Radius of Middle Bent Area $\approx$ 26.5 cm, and Bottom Linear Area $\approx$ 7 cm.

This mode of refuse collection is complemented by object detection capabilities, ensuring swift and efficient servicing of the robot. This integration minimizes operational downtime during cleaning procedures, enhancing the overall efficiency of the refuse collection mechanism.

B. Sieving Shaker Mechanism

The sieving shaker mechanism *(Fig. 5)* comprises a sand director with dimensions of 32 cm by 4 cm, designed to elevate debris to the sieve area. A vibrating mesh, measuring 32 cm by 40 cm with a height of 6 cm, is deployed to sift through sand effectively while retaining solid waste. Given the need for robustness in the components, parts for this mechanism are fabricated using steel and sheet metal.

The fabricated sieving shaker features the following parameters: Sieve Frame dimensions are 40 cm x 36.5 cm, Vibrating Mesh dimensions are 30 cm x 24.5 cm, each cell of the mesh measures 5 mm x 5 mm, Vibration Amplitude is 1 cm, and Vibration Frequency is 2.5 Hz (150 rpm).

This mode of refuse collection primarily targets the capture of larger debris categories, including plastics (if missed by the raking mechanism), glass, wrappers, and driftwood, while allowing smaller sand particles to pass through. The collected refuse is subsequently transported to a designated storage compartment for subsequent disposal.

C. Systems and Functionalities

Fig. 7 Constructed Prototype of Beach Cleaning Robot

Overview of Prototype Configuration *(Fig. 7)* - Our prototype depicted is equipped with two separate Arduino controllers. One Arduino controller governs the operation of the raking mechanism, while the other controls the sieving shaker mechanism. Both Arduino controllers are interconnected via I2C communication to facilitate seamless integration with a common navigation subsystem.

Fig. 8 shows the control system of navigation and refuse collection mechanisms with suitable motors and their controller components.

Navigation System - The primary navigation system of the robot employs DC motors to drive the front wheels. These motors are controlled using a Sabertooth motor driver, ensuring precise and efficient movement of the robot across various terrains.

Raking Mechanism Control - The raking mechanism is operated by two NEMA23 stepper motors, which are controlled using TB6600 motor drivers. This configuration enables precise control over the raking motion, optimizing the collection of larger debris from the beach surface.

Sieving Shaker Mechanism Control - The sieving shaker mechanism is operated using a DC gear motor coupled with a cam shaft mechanism, controlled through a relay. This setup facilitates effective sifting and separation of sand and solid waste, enhancing the efficiency of the sieving process.

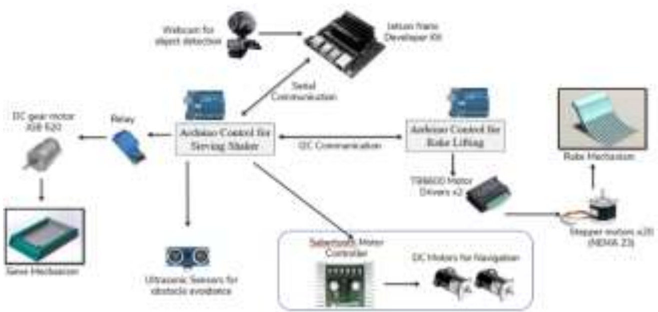

Fig. 8 System Diagram with components

Obstacle Avoidance System - In addition to the primary functionalities, we have integrated an obstacle avoidance system utilizing ultrasonic sensors. This system enhances the robot's navigational capabilities by detecting obstacles in its path and autonomously adjusting its trajectory to avoid collisions.

D. Object Identification and Distance Estimation

Training of YOLOv5 Model - We employed the YOLOv5 model, trained on a dataset comprising 16,000 images of plastic debris, to achieve a remarkable detection accuracy of 93% for plastics. Each image in the dataset was labeled with bounding boxes around plastic objects, enabling the model to accurately identify plastics in diverse beach environments.

Real-Time Object Detection Setup - For real-time object detection, the system utilizes a simple web camera. Distances to detected objects are estimated using a focal length calculation derived from reference images with known dimensions. This setup offers a viable solution for automated beach cleaning operations, despite some variation observed in distance estimation.

Focal Length Calculation - To calculate the focal length necessary for distance estimation, we utilized a simple web camera along with reference images of known object dimensions. The focal length was determined by establishing a relationship between the measured distances and the widths of objects in the reference images.

$$\text{Focal length} = \frac{Width\ in\ reference\ image * Distance\ from\ the\ camera}{Real\ width\ of\ the\ object} \quad (1)$$

Distance Estimation - With the calculated focal length from (1) and known object widths, a distance estimation function was developed. During empirical testing, some variation was observed between estimated distances and actual distances. This variation is likely attributable to factors such as camera angle and environmental conditions, which may affect the accuracy of distance estimation.

E. Predefined Path Planning

Path Navigation During Raking Mechanism Operation - During the operation of the raking mechanism, the robot follows a predetermined path while collecting plastics from the beach surface as shown in Fig. 9. Object identification is performed using the YOLOv5 model, enabling the robot to identify and collect plastics effectively as it navigates along the predefined path.

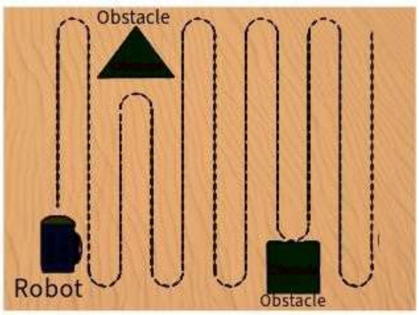

Fig. 9 Predefined Path Planning

Fig. 10 Here, shots 1-4 show the predefined path following navigation in laboratory area.

Path Navigation During Sieving Shaker Mechanism Operation - Upon activation of the sieving shaker mechanism, as shown in Fig. 10, the robot utilizes sensor inputs to navigate along a predetermined path specifically designed for the effective filtration of sand. This path ensures that the sieving shaker mechanism covers the desired area of the beach, optimizing the separation of sand and solid waste.

F. *Obstacle Avoidance with Fuzzy Logic Implementation*

Obstacle Avoidance During Navigation - During both modes of operation, the robot is equipped with an obstacle avoidance system to navigate while avoiding obstacles en route. This system enhances the robot's navigational capabilities by detecting obstacles in its path and autonomously adjusting its trajectory to avoid collisions, ensuring safe and efficient operation throughout the cleaning process.

Sensor Configuration for Obstacle Avoidance - The obstacle avoidance system utilizes two ultrasonic sensors positioned on each side of the robot. While this configuration provides basic obstacle detection capabilities, to achieve precise 180° obstacle avoidance, we propose the use of an ultrasonic sensor array with a distributed architecture. This sensor array would comprise multiple sensors strategically positioned around the robot, enhancing the effectiveness of the obstacle avoidance system.

Fuzzy Logic Implementation for Navigation - To accurately determine the turning direction of the robot when encountering obstacles, we implement fuzzy logic within the obstacle avoidance system.

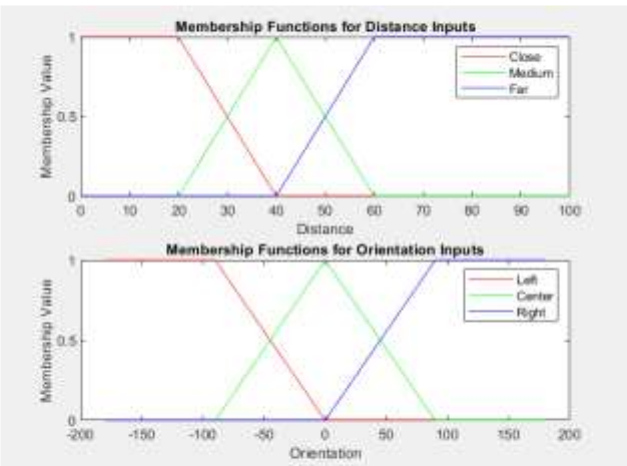

Fig. 11 Membership Functions

The fuzzy logic controller considers inputs such as the distance to the obstacle and the orientation or direction of the obstacle relative to the robot's current trajectory. As shown in Fig. 11, the membership functions were defined for the inputs. By considering these factors, the fuzzy logic controller determines the optimal turning direction for the robot, enabling it to navigate safely around obstacles with precision.

V. Results and Discussion

A. *Raking Arm Performance Analysis*

The design of the raking arm incorporates a stepper motor and pulley mechanism with a 3:1 gear ratio, enabling efficient debris acquisition from ground level. The arm rotates through an angular range of 0 to 120 degrees for a cycle of operation with a single degree of freedom (DOF).

Stepper Motor Programming and Operation - To translate the rotational motion of the rake into actionable steps, we calculated a stepping constant based on the motor's specifications, yielding a value of 0.05625. Utilizing this constant, the number of steps required for rotation was determined for both the large and small pulleys. Specifically, 2133.33 steps are needed for the large pulley, while 6400 steps are required for the small pulley. With a rake rotational speed of 3.33 rpm ($\pi/9$ rads^{-1}), debris collection is effectively executed within a 6-second timeframe. Conversely, the small pulley operates at a higher speed of 10 rpm ($\pi/3$ rads^{-1}).

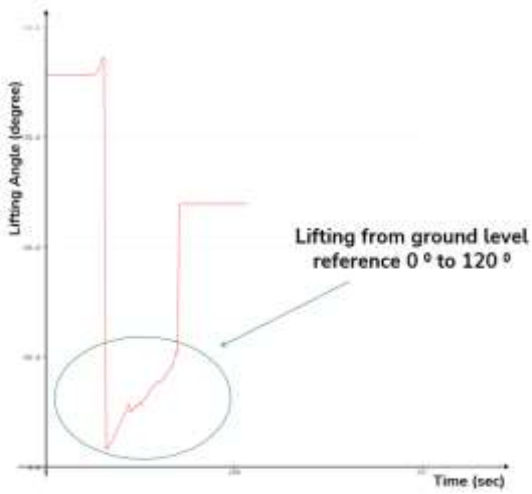

Fig. 12 Lifting angle (degree) Vs Time (Sec)

Lifting Function Analysis - To evaluate the lifting function of the raking mechanism as shown in Fig. 13, we employed a comprehensive testing approach utilizing an Inertial Measurement Unit (IMU) sensor to analyze positional changes throughout a cycle. As shown in the graph output – Fig. 12, focusing on the time required for a 120-degree lift, the calculation yielded a time of 6 seconds for completion. To ensure precision and efficiency in the lifting process, acceleration was factored in at 200 µsteps sec^{-2}. Additionally, the maximum speed attainable during the lifting motion was

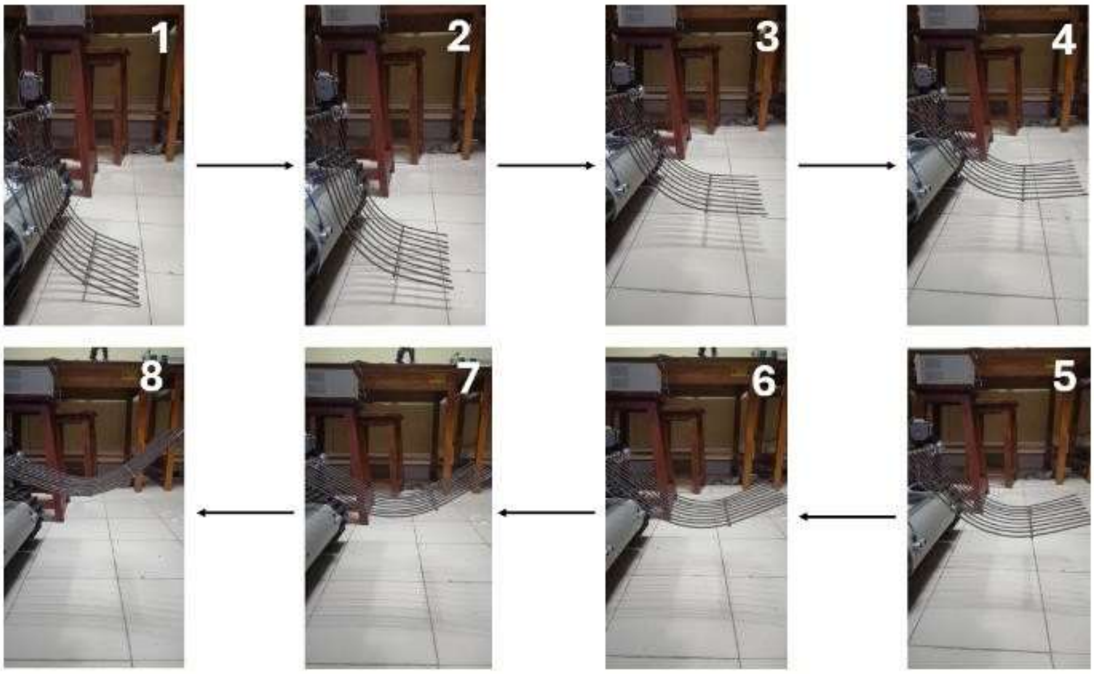

Fig. 13 Here, shots 1-8 show the lifting function of raking mechanism through 90 degrees from the ground level.

determined by multiplying the acceleration by the total time, resulting in a speed of 1200 μsteps sec^{-1}.

Discussion - The designed raking arm demonstrated effective debris collection capabilities within a 6-second timeframe, meeting the operational requirements for efficient beach cleaning. The calculated stepping constants and motor programming ensured accurate and precise motion control, optimizing the performance of the raking mechanism. Furthermore, the lifting function analysis provided valuable insights into the dynamics of the raking mechanism, highlighting the importance of acceleration and speed control for achieving efficient debris collection.

B. Sieving Shaker Performance Analysis

Frequency of Vibration Experiment - In an experiment conducted to determine the frequency of vibration for the sieving shaker mechanism, the time taken for 30 complete vibrations was recorded. The recorded times were 11.72s, 12.26s, 11.95s, 12.35s, and 11.81s. To establish a reliable average, these times were summed up and divided by the total number of observations, resulting in a mean time of 12.018 seconds for 30 vibrations.

Frequency Calculation - The average time serves as a crucial metric for calculating the frequency of vibration. By applying the formula for frequency, which involves taking the reciprocal of the time taken for one cycle of vibration, the frequency was determined to be approximately 2.5 Hz. This frequency is equivalent to 150 rpm and represents the operational speed of the sieving shaker mechanism.

Discussion - The determined frequency of approximately 2.5 Hz (150 rpm) for the sieving shaker mechanism indicates the optimal operational speed for effective sand filtration. This frequency ensures efficient sifting and separation of sand and solid waste, aligning with the design objectives of the sieving shaker mechanism. The recording and calculation of vibration times provided a reliable basis for determining the mechanism's frequency, contributing to the overall performance optimization of the sieving shaker mechanism.

The established frequency of 2.5 Hz (150 rpm) serves as a crucial parameter for the design and operation of the sieving shaker mechanism. It ensures that the mechanism operates at an optimal speed, facilitating effective sand filtration while minimizing energy consumption. Furthermore, this frequency determination underscores the importance of experimental validation in confirming the performance parameters of robotic mechanisms, enhancing the reliability and efficiency of the sieving shaker mechanism for beach cleaning applications.

C. Object Detection Analysis

The integrated system demonstrated exceptional performance in real time object detection as shown in Fig. 15, with the trained YOLOv5 model achieving an accuracy of 93% *(Fig. 14)* in detecting plastic debris. Despite the variation observed in distance estimation, the system offers a viable solution for automated beach cleaning operations. Further refinement and calibration may be necessary to minimize distance estimation errors and enhance overall system performance.

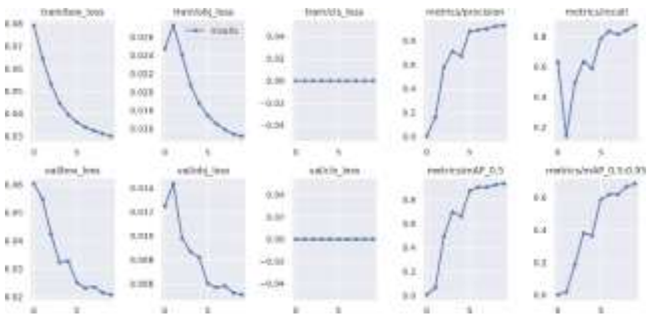

Fig. 14 Accuracy output from trained YOLO model

Fig. 15 Real time plastic identification

VI. Future Works

A. Optimization of Mechanism Designs and Simulation Parameters

The 3D models of the mechanisms were designed according to the predetermined plan and subsequently subjected to simulation using specific parameters. Our prototype selection, driven by identified research gaps and grounded in a thorough literature review, fills the void of models with integrated essential mechanisms. To further enhance the performance and efficiency of the prototype, future work will focus on detailed analysis and optimization of optimal values for the design and simulation parameters.

B. Integration of Additional Features

While our prototype already incorporates dual modes of refuse collection mechanisms, object detection, autonomous navigation, and obstacle avoidance systems, future iterations may benefit from the integration of additional features such as machine learning algorithms for improved object recognition and adaptive navigation capabilities.

C. Object Detection Enhancement

Future work will focus on refining distance estimation algorithms and optimizing system parameters to improve accuracy and reliability. Additionally, further improvements will be implemented through detailed analysis and validation of optimal values for system components, ensuring continuous enhancement of the robot's capabilities.

VII. Conclusion

A. Mechanism Design and Prototype Development

The 3D models of the raking and sieving shaker mechanisms were designed according to predetermined specifications and subsequently validated through simulation using specific parameters. The selection of a singular prototype, driven by identified research gaps and grounded in a thorough literature review, fills the void of integrated models with essential mechanisms. Prioritizing cost-effectiveness, the prototype emerges as an innovative force in the field of beach cleaning robotics.

B. Robust Solution for Beach Cleaning

Our prototype offers a robust solution for effectively and efficiently cleaning beaches by combining dual modes of refuse collection mechanisms, advanced object detection, autonomous navigation, and obstacle avoidance systems. This comprehensive approach addresses the challenges of coastal pollution mitigation, positioning our solution as a promising tool for sustainable beach maintenance.

C. Advanced Object Detection and Distance Estimation

By integrating advanced object detection techniques with distance estimation capabilities, our beach cleaning robot offers a promising solution for mitigating plastic pollution on beaches. Despite some variation observed in distance estimation, the integrated system facilitates efficient and automated cleanup operations, enhancing the robot's performance in real-world beach environments.

VIII. References

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