INTELLIGENT BEACH CLEANING ROBOT

Barathraj M. - 190091K

Mahiliny J. - 190378X

Yathunanthanasarma B. - 190722A

Degree of Bachelor of Science in Engineering

Department of Electrical Engineering

University of Moratuwa

Sri Lanka

June 2024

INTELLIGENT BEACH CLEANING ROBOT

Barathraj M. - 190091K

Mahiliny J. - 190378X

Yathunanthanasarma B. - 190722A

Report submitted in partial fulfillment of the requirements for the

Honours Degree of Bachelor of Science in Engineering

Department of Electrical Engineering

University of Moratuwa

Sri Lanka

June 2024

1. PROJECT DECLARATION OF ORIGINALITY AND OWNERSHIP

We, the undersigned members of the Group 14, hereby declare that the project entitled "Intelligent Beach Cleaning Robot," conducted at the University of Moratuwa under the supervision of Prof. A.G.B.P. Jayasekara, is original work created by us unless otherwise indicated. We assert our ownership of the intellectual property developed during the course of this project, including but not limited to software code, hardware designs, documentation, and research findings.

We confirm that all contributions from external sources, including collaborators, advisors, and referenced materials, have been appropriately acknowledged and attributed in accordance with academic and ethical standards. Any copyrighted materials, trademarks, or proprietary information used in the project have been duly licensed, authorized, or used within the scope of fair use provisions.

Furthermore, we affirm that no part of this project infringes upon the intellectual property rights of any third party, and we bear sole responsibility for any consequences arising from the use or dissemination of the project's outputs. We understand the importance of upholding academic integrity, respecting the rights of others, and maintaining transparency in our research and development endeavors.

By signing below, we acknowledge our commitment to preserving the originality and integrity of our work and to upholding the principles of honesty, accountability, and professionalism in all aspects of the project.

Signed:

1. Barathraj M.
2. Mahiliny J.
3. Yathunanthanasarma B.

Date: 14th of July 2024

The above candidates has carried out this design project for the final year under my supervision.

Signature of the supervisor : Date :

2. ABSTRACT

Coastal pollution, exacerbated by the continuous accumulation of plastics and debris on beaches, poses a severe threat to both natural habitats and marine ecosystems. This pollution disrupts the delicate balance of coastal environments, endangering wildlife and diminishing the aesthetic and economic value of these areas. Despite the dedication of manual cleaning efforts, these methods are labor-intensive and insufficient to combat the scale and persistence of the problem. As a response to this growing environmental crisis, the development and deployment of intelligent beach cleaning robots presents a promising and innovative solution that merges advanced technological capabilities with environmental conservation goals.

This project focuses on examining current robotic refuse collection mechanisms and introduces an Intelligent Beach Cleaning Robot specifically designed to tackle coastal pollution. The robot is equipped with dual modes of refuse collection mechanisms, namely raking and a sieving shaker, to ensure comprehensive cleaning. Additionally, it incorporates advanced object detection capabilities using the YOLOv5 model, autonomous navigation, and sophisticated obstacle avoidance systems to enhance its operational efficiency and effectiveness.

Through rigorous testing and analysis, the project has achieved notable success, with an accuracy rate of 93% in detecting plastic debris. The YOLOv5 model, a state-of-the-art object detection system, has been instrumental in distinguishing between different types of waste, ensuring that the robot effectively targets and collects plastic pollutants. The raking mechanism of the robot has demonstrated its capability to gather debris efficiently, operating within a 6-second timeframe. Concurrently, the sieving shaker mechanism has been optimized to function at a frequency of 2.5 Hz, which has proven effective for the filtration of sand and separation of smaller particles.

The prototype of this Intelligent Beach Cleaning Robot aims to significantly enhance refuse collection capabilities in a cost-effective manner. By addressing the critical need for adaptable and efficient beach cleaning solutions, this project contributes to the broader efforts of environmental preservation and sustainable management of coastal areas. The integration of advanced technology in beach cleaning not only improves the efficacy of waste removal but also reduces the dependency on manual labor, paving the way for a cleaner and healthier coastal environment.

3. ACKNOWLEDGEMENTS

We would like to express our sincere gratitude to all those who have supported and contributed to the successful completion of this project.

First and foremost, we are deeply thankful to our supervisor, A.G.B.P. Jayasekara, whose invaluable supervision and advice have been instrumental in redefining and enhancing the objectives and methodologies of this project. His guidance, patience, and continuous support have been crucial throughout the research and development phases.

We are also grateful to the staff of the Mechanical Engineering Department Workshop for their assistance with the mechanical design aspects of the project. Their expertise and resources have significantly contributed to the construction and functionality of the apparatus used in this research.

A special thanks to our fellow students for their collaborative spirit and assistance in the collection of materials and data, as well as for their valuable insights during various stages of the project.

Additionally, we would like to acknowledge the partial funding provided by the University, which has facilitated the procurement of necessary resources and equipment for this project. This financial support has been pivotal in enabling the practical implementation of the research.

Finally, we extend our appreciation to all external bodies and others who have provided data, materials, and moral support, contributing to the successful realization of this project.

Thank you all for your unwavering support and encouragement.

Sincerely,

Barathraj M. - 190091K

Mahiliny J. - 190378X

Yathunanthanasarma B. - 190722A

4. TABLE OF CONTENTS

5. LIST OF FIGURES

6. LIST OF TABLES

7. 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 valiant 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.

Here, we advocate 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 stewardship, these robots aim to safeguard our beaches and marine ecosystems while reducing the burden on human labor.

8. 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.

9. WORK BREAKDOWN STRUCTURE (WBS) / TIMELINE

9.1. **Project Initiation Phase** (2 weeks)

- Define project objectives and scope
- Identify team roles and responsibilities
- Set up project communication channels
- Conduct kickoff meeting to align team members
- Review and finalize project plan

9.2. **Research and Planning Phase** (4 weeks)

- Conduct literature review on existing beach cleaning robots
- Define technical requirements and specifications
- Research and select appropriate materials and components
- Plan and design the mechanical components
- Plan and design the electrical and control systems
- Plan and design the software architecture

9.3. **Mechanical Design and Fabrication Phase** (10 weeks)

- Finalize design of raking mechanism
- Fabricate raking mechanism components
- Assemble and test raking mechanism
- Finalize design of sieving shaker mechanism
- Fabricate sieving shaker mechanism components
- Assemble and test sieving shaker mechanism

9.4. **Electrical and Control System Development Phase** (8 weeks)

- Procure necessary electronic components
- Design and program Arduino controllers
- Integrate motor drivers and sensors
- Test individual subsystems
- Integrate subsystems and conduct integration testing

9.5. **Software Development Phase** (8 weeks)

- Collect and annotate dataset for object detection
- Train and optimize YOLOv5 model
- Develop algorithms for distance estimation
- Implement control algorithms for autonomous navigation
- Integrate software with hardware components
- Conduct software testing and debugging

9.6. **Integration and Testing Phase** (4 weeks)

- Integrate mechanical, electrical, and software components
- Conduct system-level testing and validation
- Perform field testing in simulated beach environment

9.7. **Documentation and Finalization Phase** (1 week)

- Document project process, design decisions, and results

10. TEAM MEMBERS' CONTRIBUTIONS

1. **Barathraj M.**

- **Goal -** To oversee the technical development and integration of the raking mechanism into the robot platform.
- **Plan -** Lead the design and fabrication of the raking mechanism, ensuring compliance with project requirements and seamless integration with the robot platform.
- **Strategy -** Collaborate closely with the team members to optimize the raking mechanism's performance through thorough testing and analysis. Responsible for programming and fine-tuning stepper motors for precise raking motion control.
- **Key Contributions**
    - Mechanical Design and Fabrication: Led the design and fabrication of the raking mechanism, including conceptualization, CAD modeling, and oversight of fabrication.
    - System Integration: Played a crucial role in integrating mechanical components with electrical and software systems to ensure the overall system's seamless functionality.
    - Testing and Validation: Conducted rigorous testing and validation of mechanical subsystems, identifying, and resolving issues to optimize performance.

2. **Yathunanthanasarma B.**

- **Goal -** To spearhead the development and implementation of the sieving shaker mechanism for efficient sand filtration.
- **Plan -** Lead the design and fabrication of the sieving shaker mechanism, ensuring compatibility with the raking mechanism and enhancing overall refuse collection capabilities.
- **Strategy -** Work closely with Barathraj to ensure compatibility between the raking and sieving mechanisms, focusing on optimizing vibration frequency and mesh design for effective sand filtration. Oversee integration of DC gear motor and cam shaft mechanism, conducting rigorous testing for performance validation.
- **Key Contributions**
    - Documentation and Reporting: Compiled comprehensive documentation of electrical designs, sensor configurations, and system specifications for knowledge transfer and project continuity.
    - Sensor Integration: Integrated ultrasonic sensors for obstacle detection and avoidance, optimizing sensor placement and calibration.
    - Focused on a part of navigation systems for autonomous operation of the robot on the beach surface.

3. **Mahiliny J.**

- **Goal -** To oversee the development and integration of object detection and distance estimation and part of navigation systems for autonomous operation.
- **Plan -** Lead implementation of YOLOv5 object detection model and navigation algorithms, enabling autonomous debris identification and navigation on the beach.
- **Strategy -** Collaborate with team members to integrate object detection and navigation systems with raking and sieving mechanisms, ensuring seamless operation and coordination. Focus on optimizing YOLOv5 model for accurate debris detection and refining obstacle avoidance algorithms for safe traversal on beach terrain.

- **Key Contributions**

    - Software Development: Led development of software algorithms for object detection, distance estimation, and autonomous navigation, leveraging expertise in computer vision and robotics.

11. SYSTEM OVERVIEW

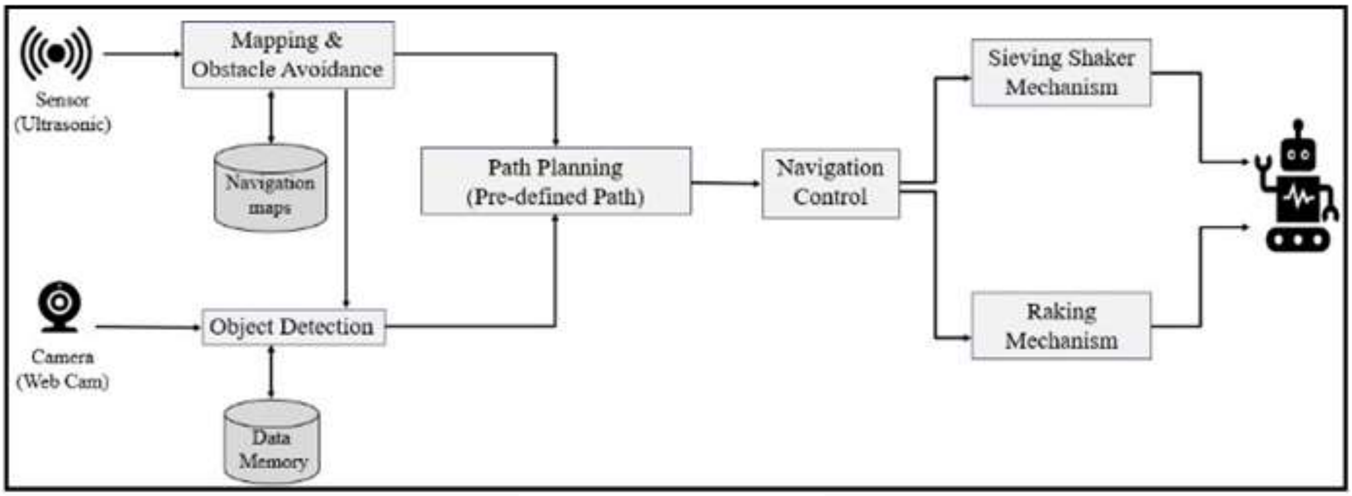


Fig. 1 System Overview

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.

12. ROBOT'S DESIGN FEATURES

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 (fig. 2, fig. 3) and fabricated using stainless steel material.

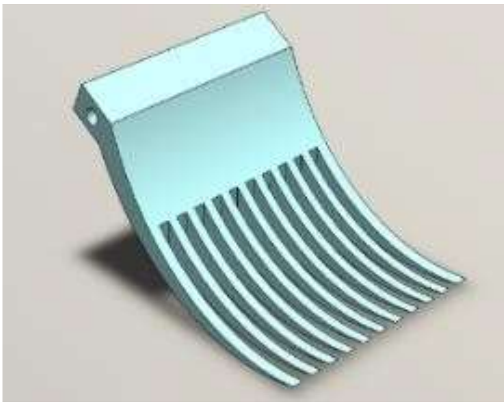


Fig. 2 Design of Rake

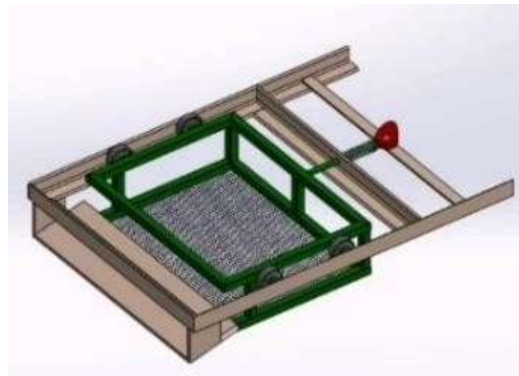
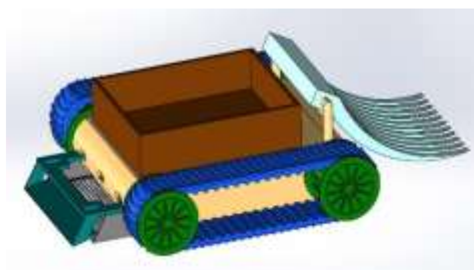


Fig. 3 Design of Sieving Shaker



12.1. Raking Mechanism

The raking mechanism 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. 4.

Fig. 4 Fabricated Rake

Fig. 5 shows the design parameters of the raking mechanism which 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 ≈ 16 cm, Radius of Middle Bent Area ≈ 26.5 cm, and Bottom Linear Area ≈ 7 cm.

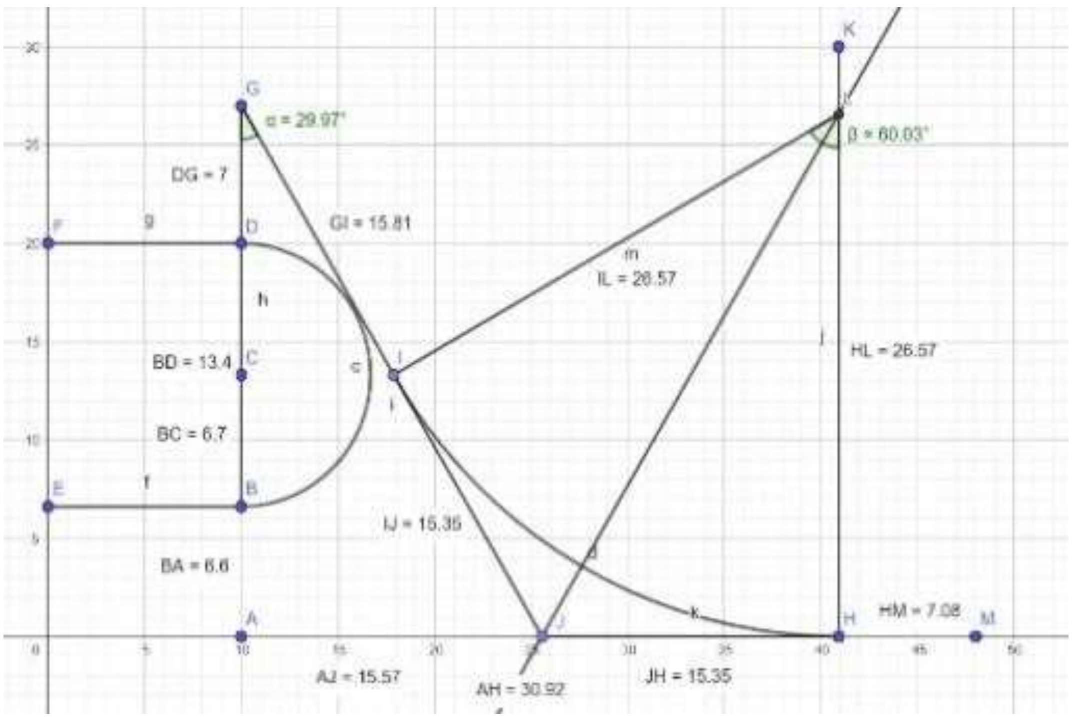


Fig. 5 Rake Design by Geometric Tool

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.

12.2. Sieving Shaker Mechanism

The sieving shaker mechanism 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 sheet metal.

The fabricated sieving shaker as shown in fig.6, 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.

Fig. 6 Fabricated Sieving shaker

12.3. 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.

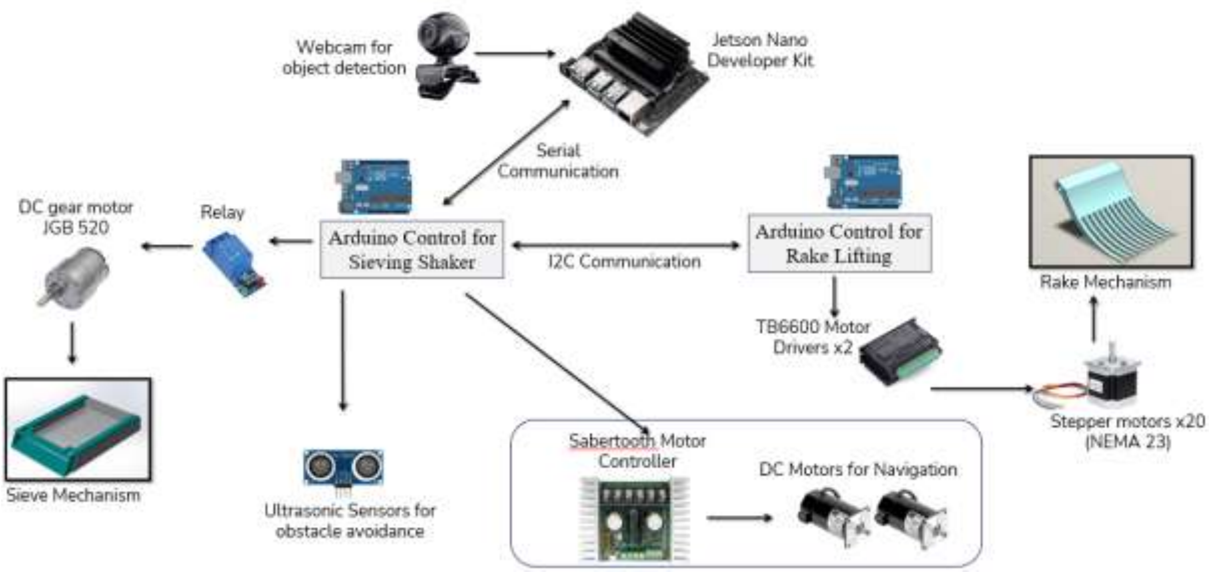


Fig. 8 System Diagram with components

- ✓ 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.
- ✓ 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.

- ✓ Object Detection – The object detection and distance estimation system utilizes a webcam connected to a Jetson Nano running a YOLOv5 model. This setup allows the robot to identify and locate objects within its environment in real-time. By processing the webcam's video feed through the YOLOv5 model, the system can detect various objects and estimate their distances.

12.4. 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.

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

- ✓ 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.

12.5. Predefined Path Planning Path

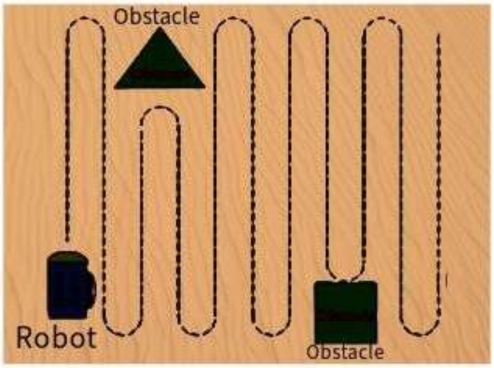


Fig. 9 Predefined Path Planning

✓ 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.

✓ 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.

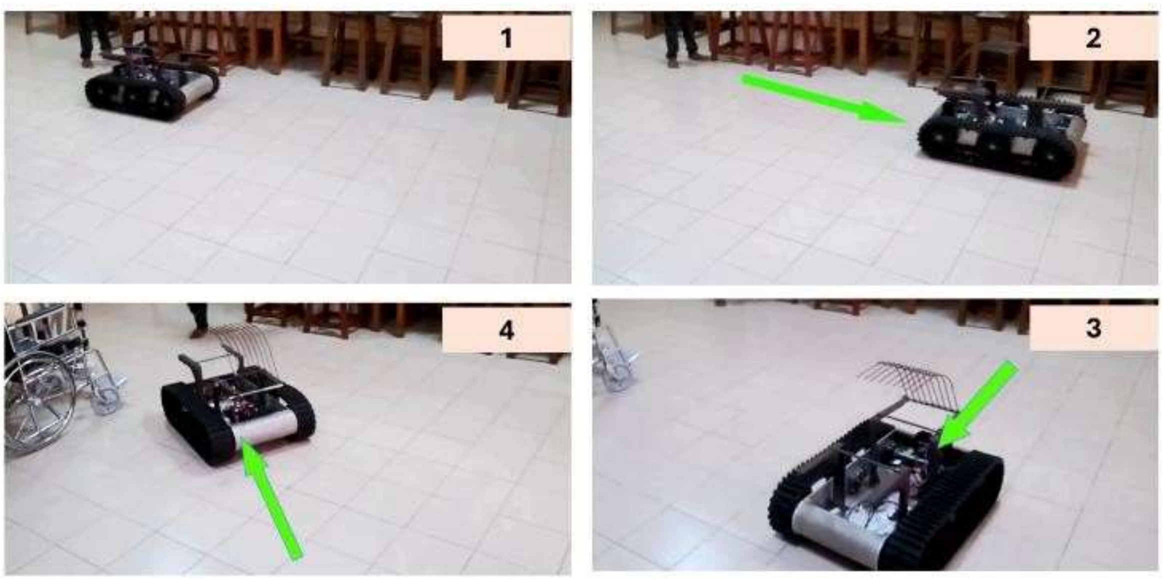


Fig. 10 Here, shots 1-4 show the predefined path following navigation in laboratory area.

12.6. Obstacle Avoidance with Fuzzy Logic Implementation

- ✓ Obstacle Avoidance During Navigation
  - o 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
  - o 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
  - o To accurately determine the turning direction of the robot when encountering obstacles, we implement fuzzy logic within the obstacle avoidance system. 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.

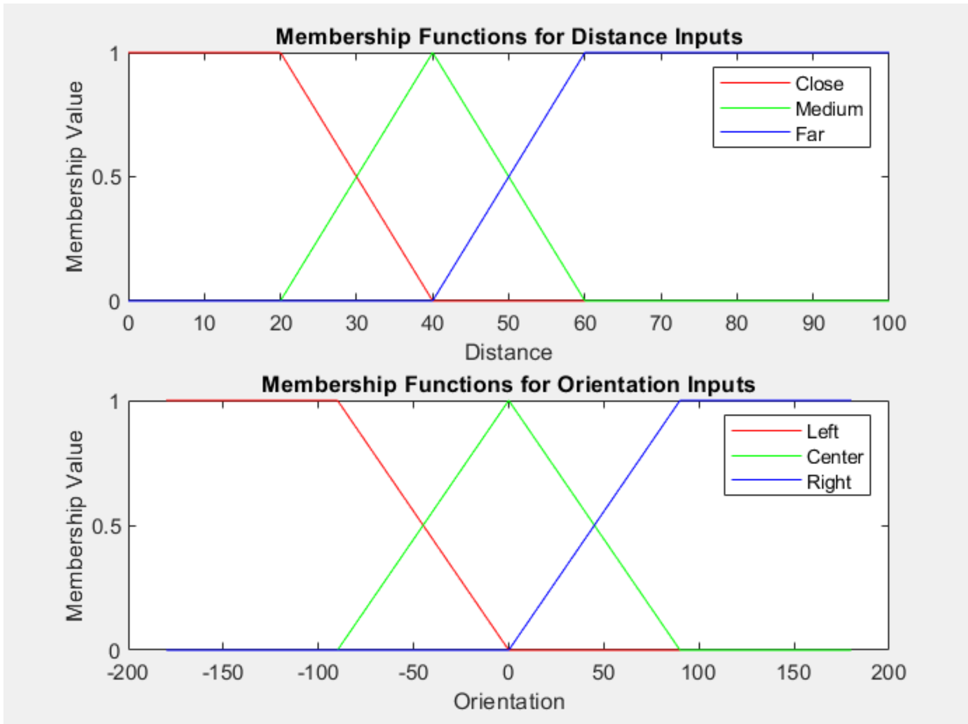
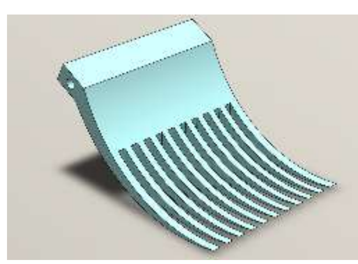


Fig.11 Membership Functions for Fuzzy Logic

13. DESIGN DECISIONS AND SELECTION

13.1. Raking Mechanism Design

- *Options Contemplated* - Different designs for the rake structure, including variations in width, length, and curvature of the rake teeth.
- *Reasons for Selected Option* - The chosen design featured a rake width of 32 cm, length of 25 cm, and a dual curve bending for efficient debris collection. This design was selected for its balance between coverage area, debris collection efficiency, and mechanical robustness.

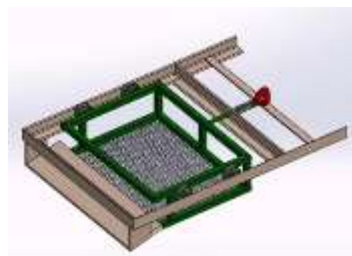
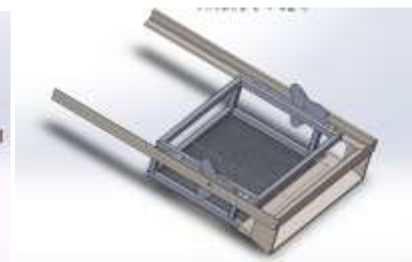


13.2. **Sieving Shaker Mechanism Design**

- *Options Contemplated* - Various configurations for the vibrating mesh, including different mesh sizes and vibration frequencies.

- *Reasons for Selected Option* - The final design included a 30 cm by 40 cm vibrating mesh with a 5 mm by 5 mm cell size and operated at a frequency of 2.5 Hz. This configuration was chosen for its optimal sand filtration capabilities while allowing smaller sand particles to pass through, thus ensuring efficient separation of solid waste from sand.

13.3. **Control System Architecture**

- *Options Contemplated* - Different microcontroller options for controlling the raking and sieving mechanisms, such as Arduino, Raspberry Pi, or custom-designed controllers.

- *Reasons for Selected Option* - Arduino controllers were chosen for their ease of programming, availability of libraries for motor control, and compatibility with various sensors. Additionally, Arduino's affordability and widespread use made it a practical choice for the project's budget and timeline constraints.

13.4. **Object Detection Algorithm**

- *Options Contemplated* - Consideration of different object detection models, including YOLOv3, YOLOv4, and custom-trained models.

- *Reasons for Selected Option* - YOLOv5 was chosen for its balance between detection accuracy, speed, and ease of implementation. Its compatibility with lightweight hardware made it suitable for real-time object detection on the beach cleaning robot without compromising performance.

13.5. **Navigation System**

- *Options Contemplated* - Various navigation methods, including GPS-based navigation, LiDAR-based SLAM (Simultaneous Localization and Mapping), and camera-based visual odometry.
- *Reasons for Selected Option* - Camera-based visual odometry was selected for its simplicity, cost-effectiveness, and compatibility with the object detection system. By analyzing visual cues from the environment, the robot could navigate autonomously without relying on external infrastructure like GPS or LiDAR, making it suitable for beach environments with varying terrains and obstacles.

13.6. **Obstacle Avoidance System**

- *Options Contemplated* - Different sensor options for detecting obstacles, such as ultrasonic sensors, LiDAR, or infrared sensors.
- *Reasons for Selected Option* - Ultrasonic sensors were chosen for their simplicity, low cost, and effectiveness in detecting obstacles within close range. They provided sufficient coverage around the robot and could be easily integrated into the existing control system for autonomous obstacle avoidance.

14. DESIGN CONSIDERATIONS, TRADEOFFS AND KEY FEATURES

14.1. **Mechanical Design**

- Tradeoff - Balancing the size and weight of the robot for maneuverability and efficiency while ensuring structural integrity and durability.
- Key Feature - Robust chassis construction using lightweight yet durable materials such as stainless steel or composite materials to withstand harsh beach environments.

14.2. **Refuse Collection Mechanisms**

- Tradeoff - Choosing between different collection mechanisms (e.g., raking, vacuuming, or scooping) based on effectiveness, power consumption, and complexity.

- Key Feature - Dual-mode collection system with raking mechanism for surface-level debris and sieving shaker mechanism for sand filtration, providing versatility in cleaning capabilities.

14.3. **Navigation and Obstacle Avoidance**

- Tradeoff - Balancing accuracy and complexity in navigation algorithms to ensure efficient path planning while avoiding collisions with obstacles.
- Key Feature - Fusion of sensor data from ultrasonic sensors and cameras for real-time environment mapping, enabling adaptive navigation and obstacle detection.

14.4. **Object Recognition and distance estimation.**

- Tradeoff - Selecting between different object detection techniques (e.g., computer vision, ultrasonic sensors) based on accuracy, speed, and computational complexity. For the distance estimation, traditional distance estimation using focal length, and using depth estimation model trained using CNN deep learning techniques.
- Key Feature - Integration of machine learning algorithms for real-time object detection and classification, enabling the robot to identify and collect specific types of debris with high accuracy. Also, for the distance estimation, using depth estimation model is better compared to traditional distance estimation methods.

14.5. **Power Management and Efficiency**

- Tradeoff - Balancing power consumption and operational runtime to optimize cleaning efficiency while ensuring sufficient battery life.
- Key Feature - Energy-efficient motor and actuator designs coupled with intelligent power management systems to maximize operational uptime and minimize recharging intervals.

14.6. **Safety Considerations**

- Tradeoff - Prioritizing safety features without compromising cleaning effectiveness or operational efficiency.
- Key Feature - Implementation of collision detection using ultrasonic sensors and emergency manual stop mechanisms to prevent accidents and protect both users and

bystanders from harm. Additionally, incorporating fail-safe mechanisms to ensure safe operation in case of system malfunctions.

14.7. **Environmental Impact**

- Tradeoff - Maximizing cleaning efficiency may involve using more aggressive mechanisms that could potentially disturb the beach ecosystem, such as deeper raking or stronger vibration for sand filtration.
- Key Feature - Implementation of ultrasonic sensors to detect sensitive areas, allowing the robot to avoid such areas during cleaning operations, minimizing ecological disturbance.

15. TECHNICAL CHALLENGES AND RESOLVE

15.1. **Integration of Dual-mode Refuse Collection Mechanisms**

- Challenge - Integrating and synchronizing the operation of the raking mechanism and sieving shaker mechanism to ensure seamless transition and optimal cleaning performance.
- Solution - Developed a robust control system architecture utilizing Arduino controllers and motor drivers to coordinate the operation of both mechanisms. Conducted thorough testing and calibration to fine-tune synchronization and optimize cleaning efficiency.

15.2. **Object Recognition and Distance estimation**

- Challenge - Achieving accurate and reliable detection of various types of debris on the beach, including plastics, glass, and organic materials, under varying lighting and environmental conditions. Also, for the distance estimation model of CNN, creating depth map can have some errors based on the lighting condition.
- Solution - Implemented a deep learning-based object detection system using the YOLOv5 model trained on a diverse dataset of beach debris images. Utilized transfer learning techniques and data augmentation to improve model accuracy and robustness.

15.3. **Power Management and Energy Efficiency**

- Challenge - Optimizing power consumption and maximizing operational runtime to ensure prolonged cleaning sessions without frequent recharging.
- Solution - Employed energy-efficient motor and actuator designs, coupled with intelligent power management algorithms, to minimize power usage during operation. Implemented sleep modes and low-power standby states to conserve energy when idle.

15.4. **Environmental Adaptability and Robustness**

- Challenge - Designing the robot to withstand harsh beach conditions, including saltwater exposure, sand ingress, and high winds, while maintaining reliability and performance.
- Solution - Utilized corrosion-resistant materials and sealed enclosures to protect sensitive components from environmental hazards. Conducted extensive durability testing and environmental simulations to validate the robot's resilience and robustness in real-world conditions.

15.5. **Real-time Data Processing and Decision-making**

- Challenge - Processing sensor data and making rapid decisions in real-time to enable responsive and adaptive behavior in dynamic beach environments.
- Solution - Implemented parallel processing techniques and optimized algorithms for efficient sensor data fusion and decision-making. Leveraged microcontroller-based systems with low-latency communication protocols to ensure timely execution of control commands.

16. RESULTS AND DISCUSSION

16.1. 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).

16.1.1. Stepper Motor Programming and Operation

To translate the rotational motion of the rake into actionable steps as shown in fig. 12, 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}).

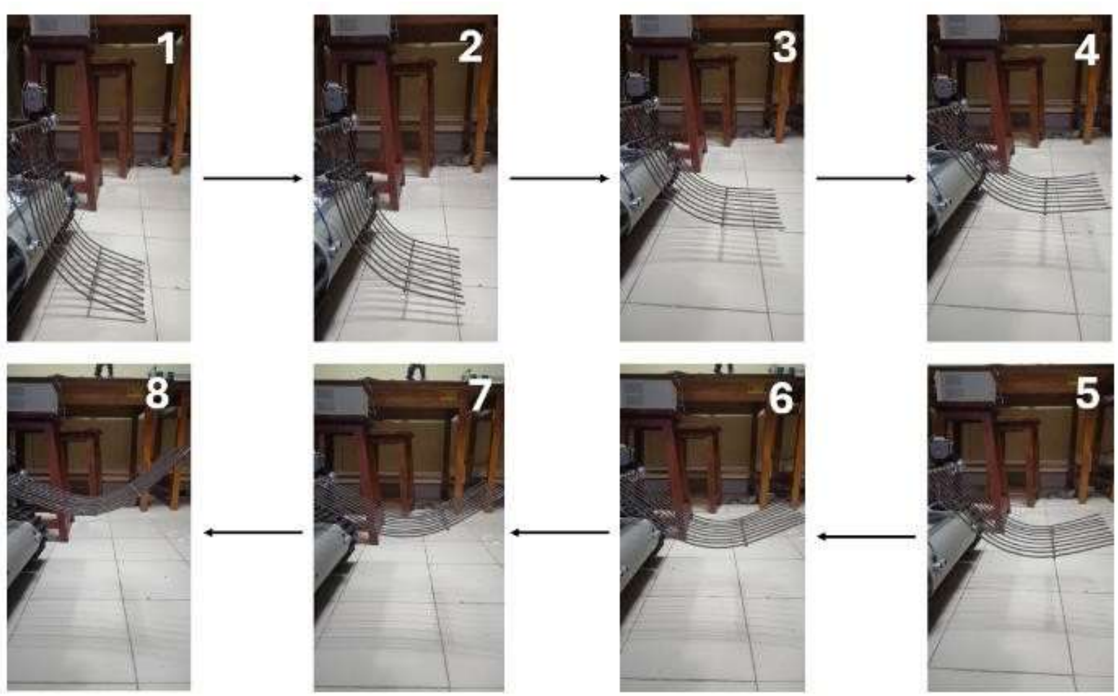


Fig. 12 Here, shots 1-8 show the lifting function of raking mechanism through 90 degrees from the ground level.

16.1.2.Lifting Function Analysis

Description	**Large Pulley**	**Small Pulley**
Angle Rotation	120	360
Steps input in the code	120 / 0.05625 = 2133.33 steps	360 / 0.05625 = 6400 steps
Speed of rotation (in rpm)	3.33 rpm	10 rpm
Speed of rotation (in degree per sec)	$\pi/9$ rads^{-1} (20 ^{o} per sec)	$\pi/3$ rads^{-1} (60 ^{o} per sec)

Table 1 Lifting function analysis

To evaluate the lifting function of the raking mechanism, 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. 13, 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 determined by multiplying the acceleration by the total time, resulting in a speed of 1200 µsteps sec^{-1}.

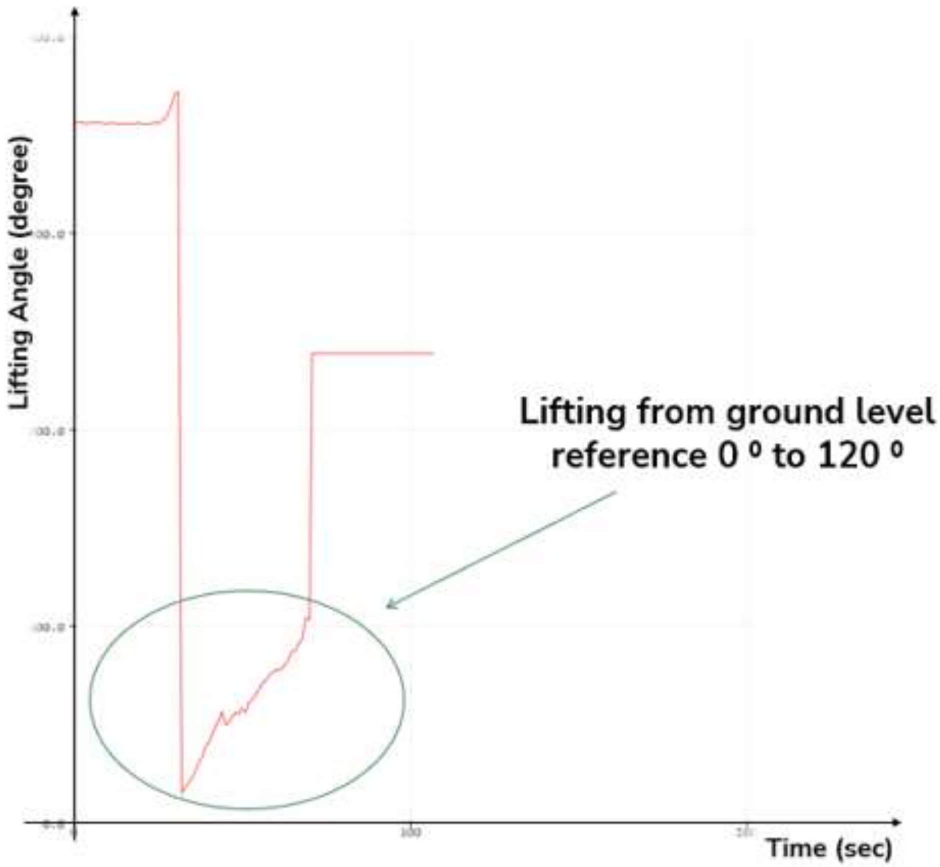


Fig. 13 Lifting angle (degree) Vs Time (Sec)

16.1.3. 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.

16.2. Sieving Shaker Performance Analysis

16.2.1. 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.

16.2.2. 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.

16.2.3. Discussion

This frequency indicates the optimal operational speed for effective sand filtration. It 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 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.

16.3. Object Detection Analysis

The integrated system demonstrated exceptional performance in real time object detection as shown in fig. 14, with the trained YOLOv5 model achieving an accuracy of 93%, depicted in fig. 15, 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 Real-time plastic identification

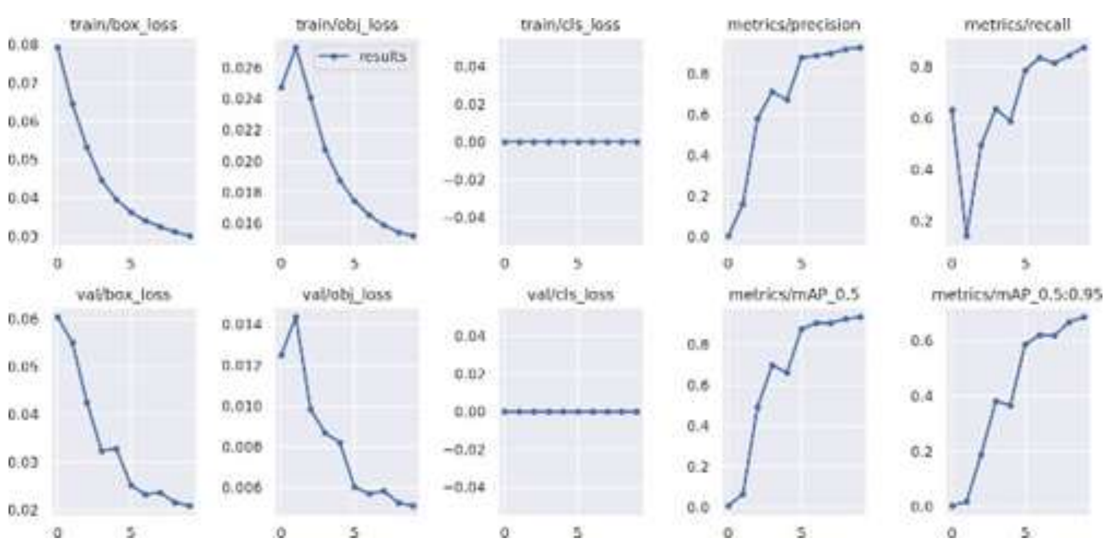


Fig. 15 Accuracy output from trained YOLO model

We tried two different approaches to find the distance from the camera to the bottle, the methods are traditional computer vision method and deep learning-based depth estimation.

16.3.1. Distance Estimation Using Known Object Dimensions

Traditional distance estimation involves capturing reference images of known objects, such as a person and a bottle, at a known distance. These reference images are crucial for the next step, which is calculating the focal length. The focal length is determined using the known distance and the dimensions of the objects in the reference images. Once the focal length is established, it can be used to estimate the distance of each detected object. By measuring the object's width in the image, the distance from the camera can be calculated using the focal length.

16.3.2. Distance Estimation Using Depth Estimation Model

A depth estimation model was trained using the NYU Depth V2 dataset, The model achieved an accuracy of 89%. This model predicts a depth map from a given image. The depth estimation model was integrated with the YOLOv5 object detection pipeline. When a bottle is detected, the corresponding region in the depth map is analyzed to estimate the distance to the object. This method provides accurate distance estimation compared to the traditional approach.

16.3.3. Epoch vs Accuracy

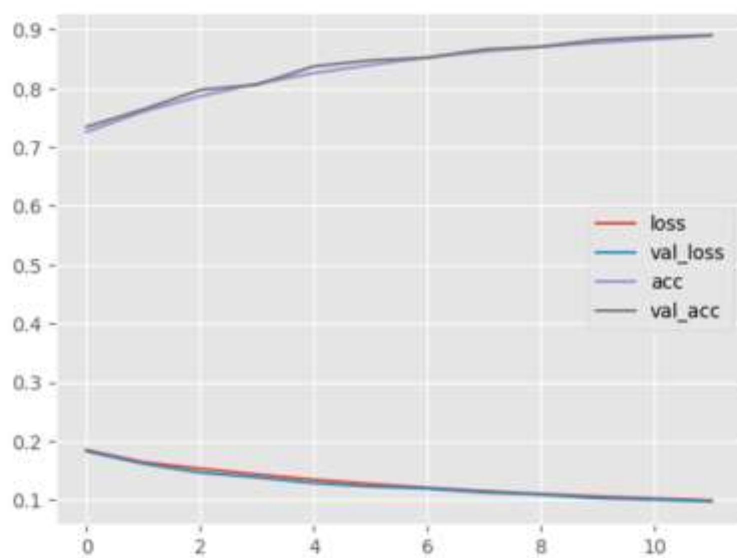


Fig. 16 NYU Depth V2 dataset after the process of depth

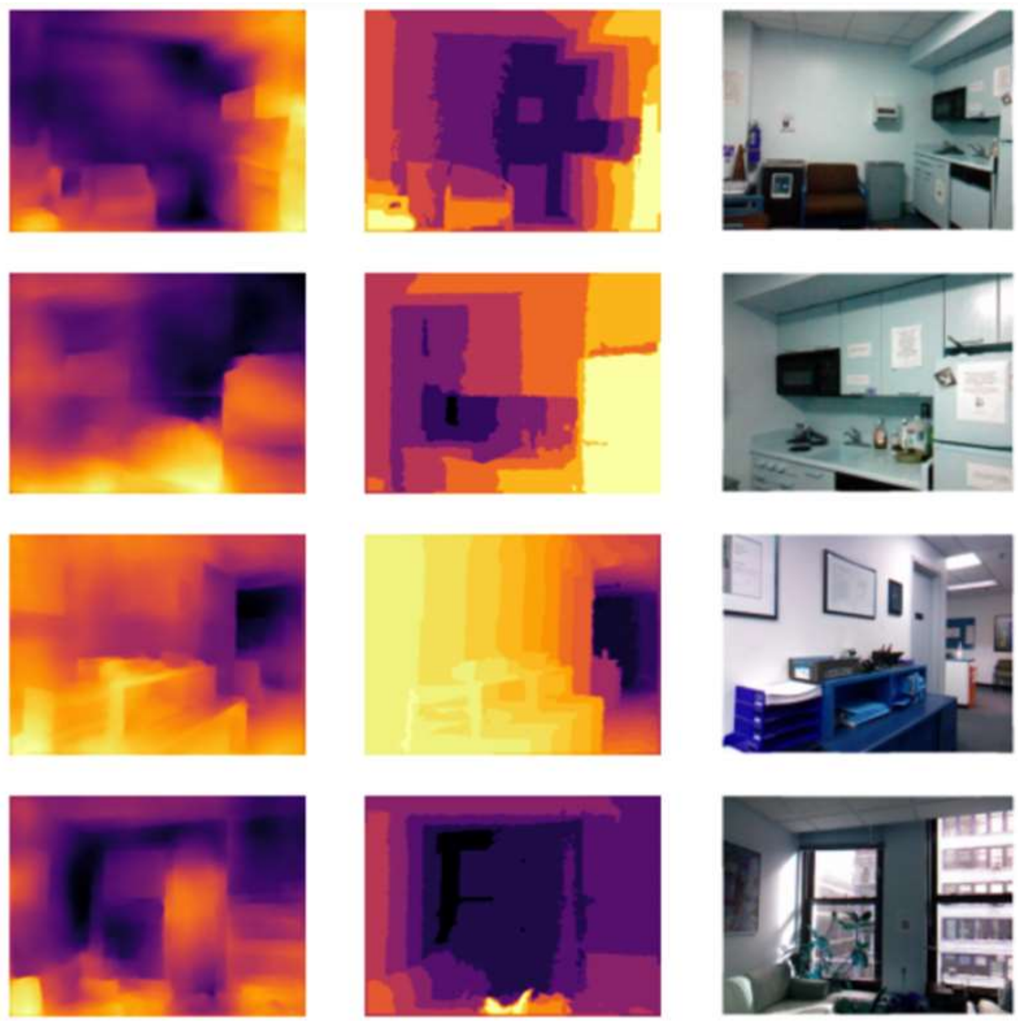


Fig. 17 Our real time depth map creation estimation

17. FURTHER IMPROVEMENT IDEAS

17.1. 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.

17.2. Distance Estimation Enhancement

Distance estimation can be enhanced by integrating stereo vision or depth-sensing cameras, such as the Intel RealSense, to obtain more accurate distance measurements. Combining data from multiple sensors, such as LIDAR or additional ultrasonic sensors, can provide a more comprehensive understanding of the environment.

18. CONCLUSION

18.1. 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.

18.2. 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.

18.3. 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.

19. INNOVATION IN THE CONTEXT OF OUR ROBOT

19.1. Novelty in Approach

The integration of dual-mode refuse collection mechanisms (raking and sieving shaker) offers a versatile solution for efficient beach cleaning, addressing the challenge of diverse debris types commonly found on beaches. Incorporation of advanced object detection using deep learning models like YOLOv5 enables real-time identification and classification of debris, enhancing the precision and effectiveness of cleaning operations.

19.2. Utility and Social Impact

The Intelligent Beach Cleaning Robot provides a practical and scalable solution to mitigate coastal pollution, helping to preserve marine ecosystems and protect wildlife habitats. By automating the cleaning process, the robot reduces reliance on manual labor, thereby alleviating the burden on human workers and potentially improving their health and safety conditions.

The robot's ability to operate autonomously and navigate through beach environments enhances the efficiency and coverage of cleaning efforts, leading to cleaner and safer beaches for communities and tourists. The solution contributes to raising awareness about environmental conservation and the importance of responsible waste management practices, fostering a culture of sustainability and stewardship among stakeholders.

19.3. Technological Limitations

The effectiveness of object detection and navigation algorithms may be affected by environmental factors such as weather conditions and terrain variability. Continuous refinement and updates to software algorithms can address these challenges over time.

19.4. Economic Considerations

The upfront cost of deploying and maintaining the robot may pose financial challenges for some communities or organizations. Cost-sharing models, grants, or subsidies could help make the technology more accessible and affordable.

20. THE COMMERCIAL VIABILITY OF OUR ROBOT PROJECT

20.1. Market Demand

There is a growing global concern about environmental conservation and the impact of pollution on coastal ecosystems. As a result, there is likely to be significant demand for innovative solutions like the Intelligent Beach Cleaning Robot that can efficiently clean beaches and mitigate the effects of pollution.

20.2. Competition

While there may be existing solutions for beach cleaning, such as manual labor or traditional beach cleaning machines, the integration of advanced technologies like object detection and autonomous navigation sets the Intelligent Beach Cleaning Robot apart from conventional methods. However, competition from other automated beach cleaning robots or technologies should be considered, and there is a higher possibility for the usage of beach cleaning robots in Sri Lanka in the near future.

20.3. Cost-effectiveness

The commercial success of the project will depend on its cost-effectiveness compared to alternative solutions. Factors such as initial investment, maintenance costs, operational efficiency, and long-term durability will influence the overall cost-benefit analysis for potential buyers or investors.

20.4. Regulatory Considerations

Compliance with environmental regulations and standards, as well as safety requirements for robotic systems, will be essential for commercial deployment. Ensuring that the Intelligent Beach Cleaning Robot meets regulatory guidelines will be crucial for market acceptance and adoption.

20.5. Potential Markets

The project may find commercial opportunities in various sectors, including government agencies responsible for beach maintenance, private beach resorts, environmental organizations, and municipalities with coastal areas. Identifying and targeting specific market segments with high demand and willingness to invest in beach cleaning solutions will be key to commercial success.

20.6. Partnerships and Collaborations

Collaborating with industry partners, research institutions, and environmental organizations can enhance the project's commercial viability by leveraging expertise, accessing funding opportunities, and expanding market reach through strategic partnerships.

21. REFERENCES

[1] D. Varghese and A. Mohan, "Binman: An Autonomous Beach Cleaning Robot," 2022 IEEE 2nd Mysore Sub Section International Conference (MysuruCon), Mysuru, India, 2022, pp. 1-5, doi: 10.1109/MysuruCon55714.2022.9972499.

[2] T. Ichimura and S. Nakajima, "Development of an autonomous beach cleaning robot “Hirottaro”," 2016 IEEE International Conference on Mechatronics and Automation, Harbin, China, 2016, pp. 868-872, doi: 10.1109/ICMA.2016.7558676.

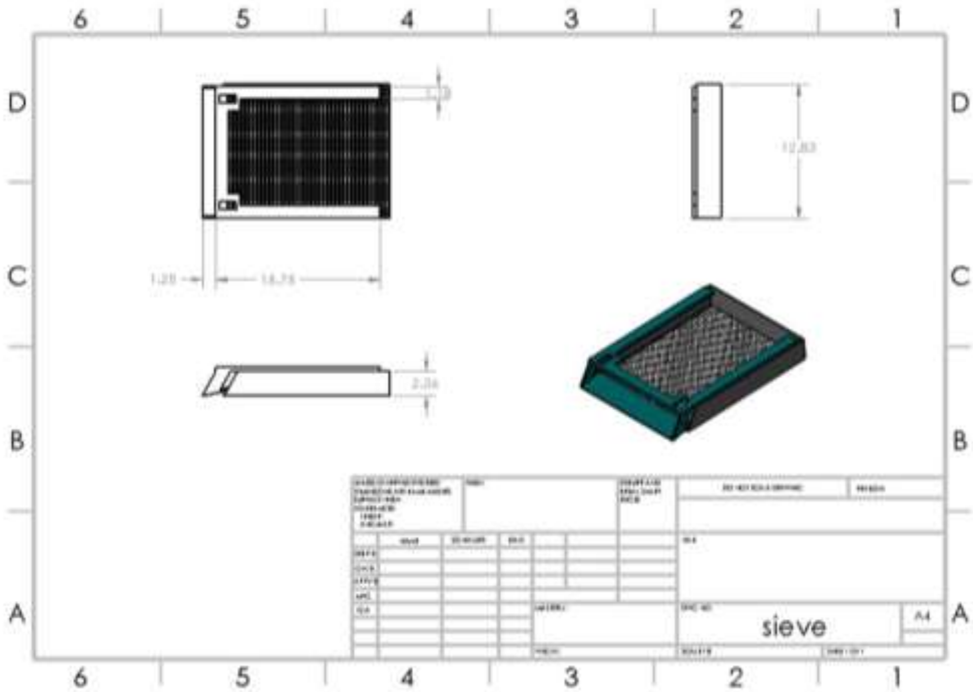
[3] Roza, Felippe & Silva, Vinicius & Pereira, Patrick & Bertol, Douglas. (2016). Modular robot used as a beach cleaner. Ingeniare. Revista chilena de ingeniería. 24. 643-653. 10.4067/S0718-33052016000400009.

[4] N. Bano et al., "Radio Controlled Beach Cleaning Bot," 2019 IEEE 6th International Conference on Engineering Technologies and Applied Sciences (ICETAS), Kuala Lumpur, Malaysia, 2019, pp. 1-6, doi: 10.1109/ICETAS48360.2019.9117269.

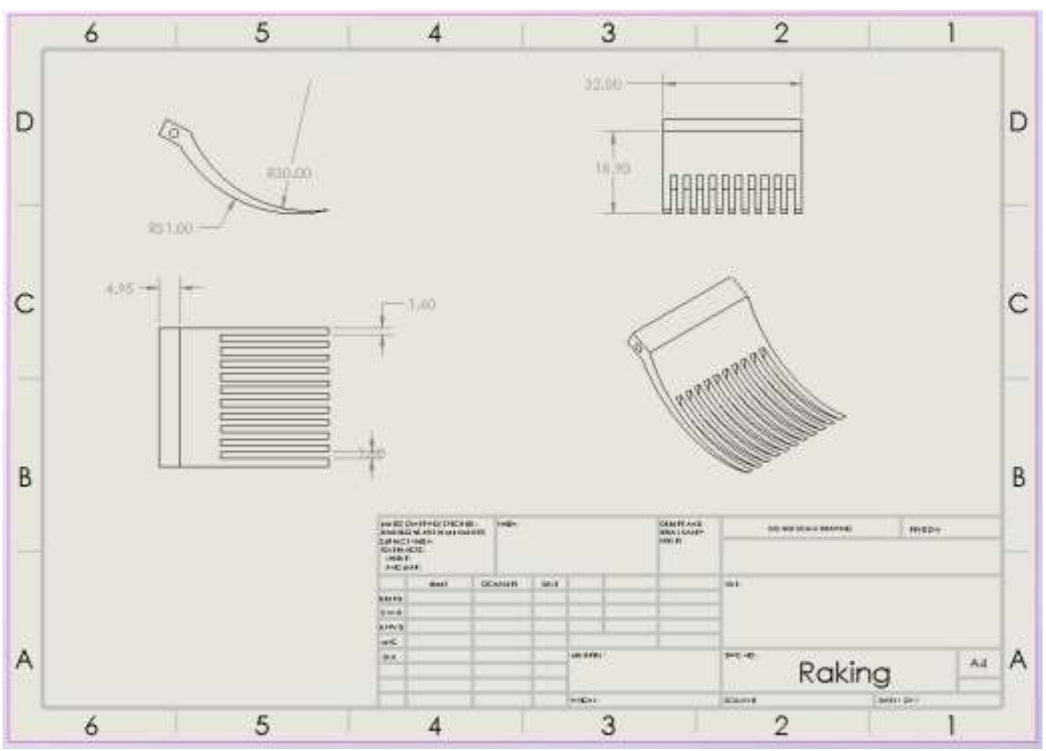
[5] J. K.A, J. S. C, L. R. M, S. K. P.S, A. Francis and A. Babu, "Deep Learning based Beach Cleaning Robot," 2023 2nd International Conference on Applied Artificial Intelligence and Computing (ICAAIC), Salem, India, 2023, pp. 427- 433, doi: 10.1109/ICAAIC56838.2023.10141099.

[6] G, Venugopal. (2020). Development of An Autonomous Beach Cleaning Robot. 49. 11-15.

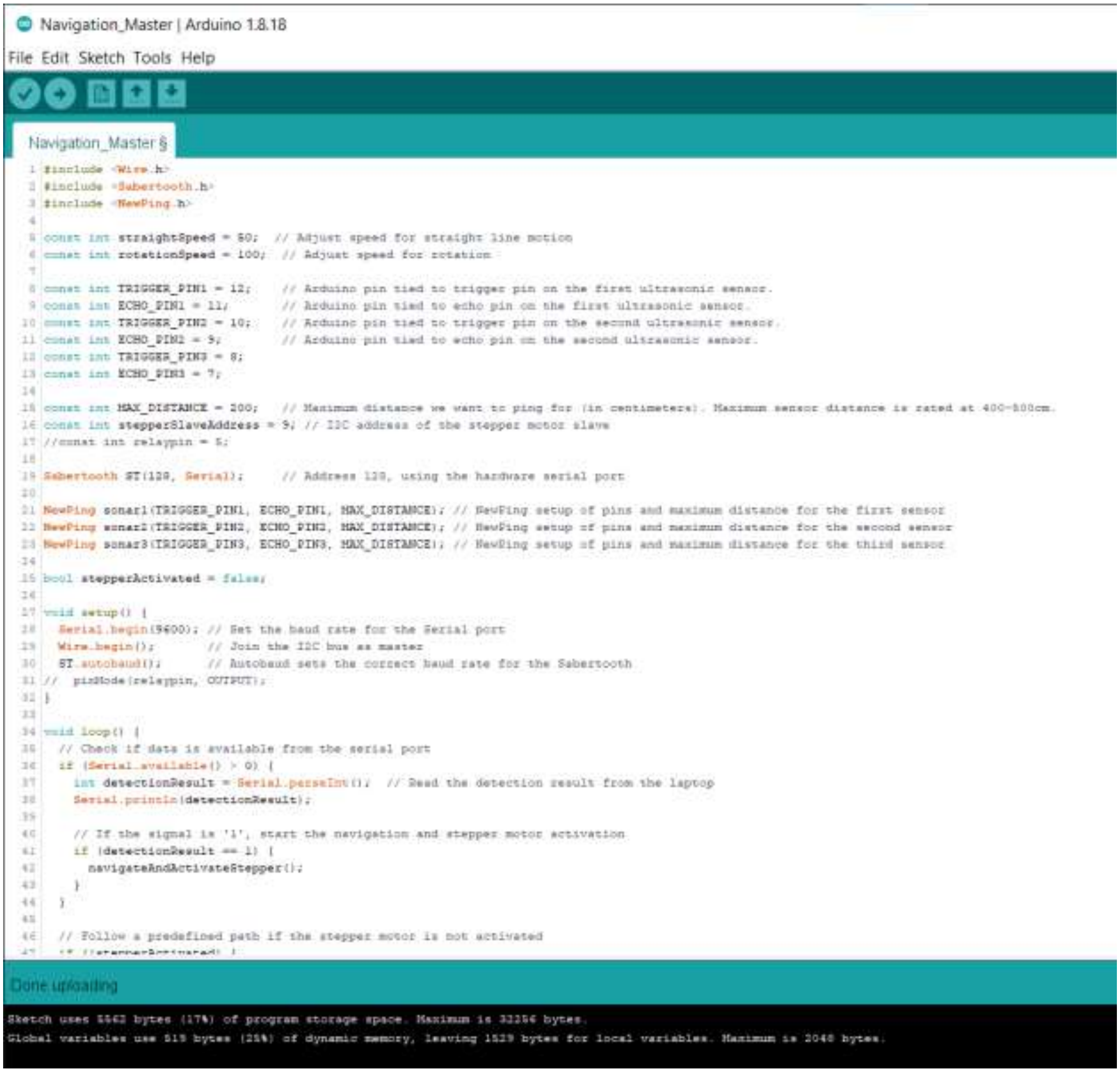
22. ANNEX



Annex 1 - Sieving Shaker Mechanical Design Parameters



Annex 2 - Rake Mechanical Design Parameters



Navigation_Master | Arduino 1.8.18

File Edit Sketch Tools Help

Navigation_Master §

```
#include <Wire.h>
#include <Sabertooth.h>
#include <NewPing.h>

const int straightSpeed = 50;  // Adjust speed for straight line motion
const int rotationSpeed = 100;  // Adjust speed for rotation

const int TRIGGER_PIN1 = 12;    // Arduino pin tied to trigger pin on the first ultrasonic sensor.
const int ECHO_PIN1 = 11;       // Arduino pin tied to echo pin on the first ultrasonic sensor.
const int TRIGGER_PIN2 = 10;    // Arduino pin tied to trigger pin on the second ultrasonic sensor.
const int ECHO_PIN2 = 9;        // Arduino pin tied to echo pin on the second ultrasonic sensor.
const int TRIGGER_PIN3 = 8;
const int ECHO_PIN3 = 7;

const int MAX_DISTANCE = 200;   // Maximum distance we want to ping for (in centimeters). Maximum sensor distance is rated at 400-500cm.
const int stepperSlaveAddress = 9; // I2C address of the stepper motor slave
//const int relaypin = 5;

Sabertooth ST(128, Serial);     // Address 128, using the hardware serial port

NewPing sonar1(TRIGGER_PIN1, ECHO_PIN1, MAX_DISTANCE); // NewPing setup of pins and maximum distance for the first sensor
NewPing sonar2(TRIGGER_PIN2, ECHO_PIN2, MAX_DISTANCE); // NewPing setup of pins and maximum distance for the second sensor
NewPing sonar3(TRIGGER_PIN3, ECHO_PIN3, MAX_DISTANCE); // NewPing setup of pins and maximum distance for the third sensor

bool stepperActivated = false;

void setup() {
  Serial.begin(9600); // Set the baud rate for the Serial port
  Wire.begin();       // Join the I2C bus as master
  ST.autobaud();      // Autobaud sets the correct baud rate for the Sabertooth
//  pinMode(relaypin, OUTPUT);
}

void loop() {
  // Check if data is available from the serial port
  if (Serial.available() > 0) {
    int detectionResult = Serial.parseInt();  // Read the detection result from the laptop
    Serial.println(detectionResult);

    // If the signal is '1', start the navigation and stepper motor activation
    if (detectionResult == 1) {
      navigateAndActivateStepper();
    }
  }

  // Follow a predefined path if the stepper motor is not activated
```

Done uploading

```
Sketch uses 5562 bytes (17%) of program storage space. Maximum is 32256 bytes.
Global variables use 519 bytes (25%) of dynamic memory, leaving 1529 bytes for local variables. Maximum is 2048 bytes.
```

Annex 3 - Arduino Code Segment for the Navigation in Master Arduino UNO

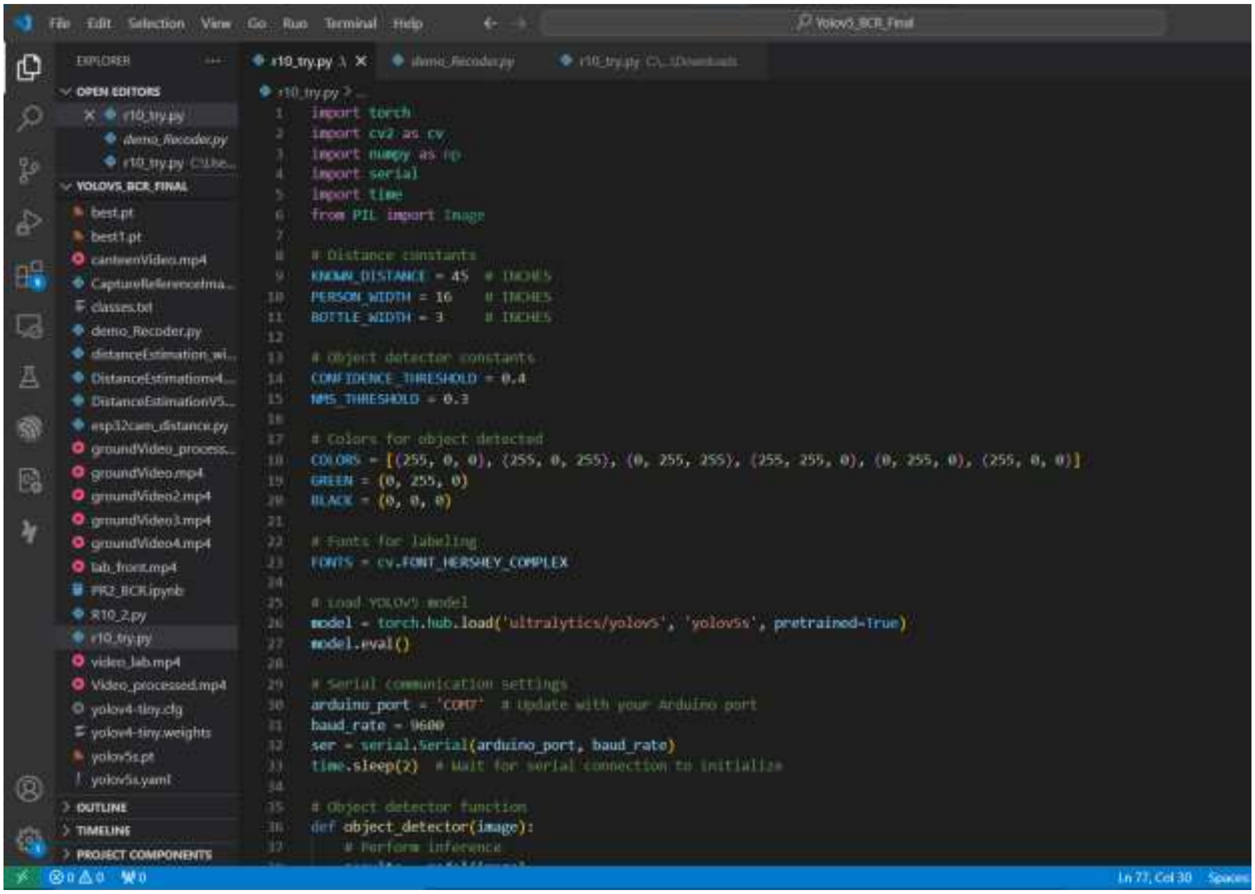

```
#include <Wire.h>
#include "AccelStepper.h"

// Define stepper motor connections and motor interface type.
// Motor interface type must be set to 1 when using a driver:
#define dirPin1 10
#define stepPin1 9
#define dirPin2 7 // Example pin numbers for the second stepper motor
#define stepPin2 6 // Example pin numbers for the second stepper motor
#define motorInterfaceType 1

// Create instances of the AccelStepper class for each motor:
AccelStepper stepper1 = AccelStepper(motorInterfaceType, stepPin1, dirPin1);
AccelStepper stepper2 = AccelStepper(motorInterfaceType, stepPin2, dirPin2);

// Global variable to store the command
volatile int command = 0;

void setup() {
  // Set the maximum speed and acceleration for each motor:
  stepper1.setMaxSpeed(900);
  stepper1.setAcceleration(150);
  stepper2.setMaxSpeed(900);
  stepper2.setAcceleration(150);

  Serial.begin(9600); // Initialize serial communication for debugging

  Wire.begin(9); // Join I2C bus with address #9
  Wire.onReceive(receiveEvent); // Register event
}

void loop() {
  // Check for the command to move the steppers
  if (command == 1) {
    Serial.println("Command received, moving steppers...");
    moveSteppers();
    command = 0; // Reset the command after processing
  }
}

void receiveEvent(int howMany) {
```

Done uploading.

```
Sketch uses 8840 bytes (27%) of program storage space. Maximum is 32256 bytes.
Global variables use 608 bytes (29%) of dynamic memory, leaving 1440 bytes for local variables. Ma
```

73

Annex 4 - Arduino Code Segment for the Stepper Motor for the Rake in Slave Arduino UNO



Annex 5 - Code Segment for the Object Recognition using YOLOv5

*****