AI enhanced Oil Recovery and Cleanup Autonomous (ORCA) system prototype with LiDAR-Based navigation and Oleophilic optimization

Stokholm Junior Water Project Report

by

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Special thanks to,

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Abstract

This project presents the design and testing of the Oil Recovery and Cleanup Autonomous (ORCA) system—a fully autonomous oil skimmer that integrates artificial intelligence, oleophilic materials, and real-time navigation to address the shortcomings of conventional oil spill response methods. Traditional approaches such as mechanical skimmers and chemical dispersants often pose environmental hazards and endanger cleanup personnel, highlighting the urgent need for scalable and intelligent alternatives.

The ORCA prototype uses a polypropylene sheet coated with silicone to enhance oil adhesion and water repellency. Testing across five oil viscosities demonstrated skimming efficiencies of 65–75.7% and water rejection rates up to 96%, confirming the material's selectivity and practical viability. An AI model trained on over 800 annotated images enabled oil detection with 97% precision and triggered skimming operations in under three seconds.

Obstacle avoidance was achieved through LiDAR and ultrasonic sensors processed by a Raspberry Pi. Experiments showed LiDAR signal quality dropped under turbulent conditions, but key targets were still reliably detected. Ultrasonic readings were stabilized using a median filtering algorithm to reject noise from water splashes, ensuring accurate navigation.

Together, these elements form a fully functional autonomous system capable of detecting and responding to oil spills without human intervention. While further testing is needed for long-term durability and large-scale deployment, this study confirms the potential of ORCA as a safer, more adaptable, and environmentally responsible alternative for marine oil spill remediation.

1. Introduction

1.1. Problem

Oil spills destroy and endanger marine ecosystems, devastate wildlife populations, and jeopardize human health. Each year, an estimated 15,000 tons of oil pollute marine environments, creating lasting ecological and economic repercussions (ITOPF, 2023). The Exxon Valdez spill of 1989 affected over 1,300 miles of Alaskan shoreline, killing 250,000 seabirds, 2,800 sea otters, 300 harbour seals, 250 bald eagles, 22 killer whales, and billions of salmon and herring eggs (Oceana, 2021). Similarly, the 2010 Deepwater Horizon spill caused unprecedented destruction, with over 82,000 birds, 25,900 marine mammals, 6,165 sea turtles, and countless fish, oysters, and coral species lost (Center for Biological Diversity, 2011). These catastrophic events highlight the urgent need for effective and sustainable solutions to mitigate the environmental destruction caused by oil spills.

1.2. Conventional solutions

Despite decades of technological advancement, existing oil spill remediation methods remain inadequate for addressing the diverse challenges posed by these disasters. Mechanical skimmers are effective in calm waters but struggle with varying oil viscosities and rough terrain. Chemical dispersants may break oil into smaller droplets but introduce toxic compounds that harm marine ecosystems and disrupt food chains. In-situ burning, while efficient at removing oil, releases harmful greenhouse gases, contributing to climate change. Together, these methods fall short of providing a scalable, adaptable, and environmentally friendly approach to oil spill remediation. However, these conventional skimmers come with a price that can often be overlooked—human lives.

1.3. Devastating Tolls

The toll of oil spills extends beyond environmental damage to the health of cleanup workers. Reports from the Deepwater Horizon response effort revealed severe health issues among workers, including respiratory problems, neurological damage, skin lesions, liver and kidney disorders, and even miscarriages. Chronic conditions, such as cancers and developmental disorders, have also been linked to prolonged exposure to oil and dispersants (Denic-Roberts, H., Engel, L.S., Buchanich, J.M. *et al,2023)*. These dangers highlight the inadequacy of manual and semi-autonomous cleanup methods, which place human lives at significant risk in hazardous environments.

1.4. Our solution

In response to these challenges, this study aims to explore the development of an autonomous oil skimmer as a potential solution for scalable, efficient, and sustainable oil spill remediation. Oil Recovery and Cleanup Autonomous (ORCA) system investigates the integration of modern technologies and advanced materials, this research seeks to address the critical shortcomings of existing methods, particularly the reliance on human intervention in hazardous conditions. The focus is on designing a system capable of operating autonomously in complex spill scenarios, reducing the risks faced by cleanup workers while maximizing oil recovery efficiency. This study represents a step towards innovative solutions to mitigate the environmental and human impacts of oil spills effectively.

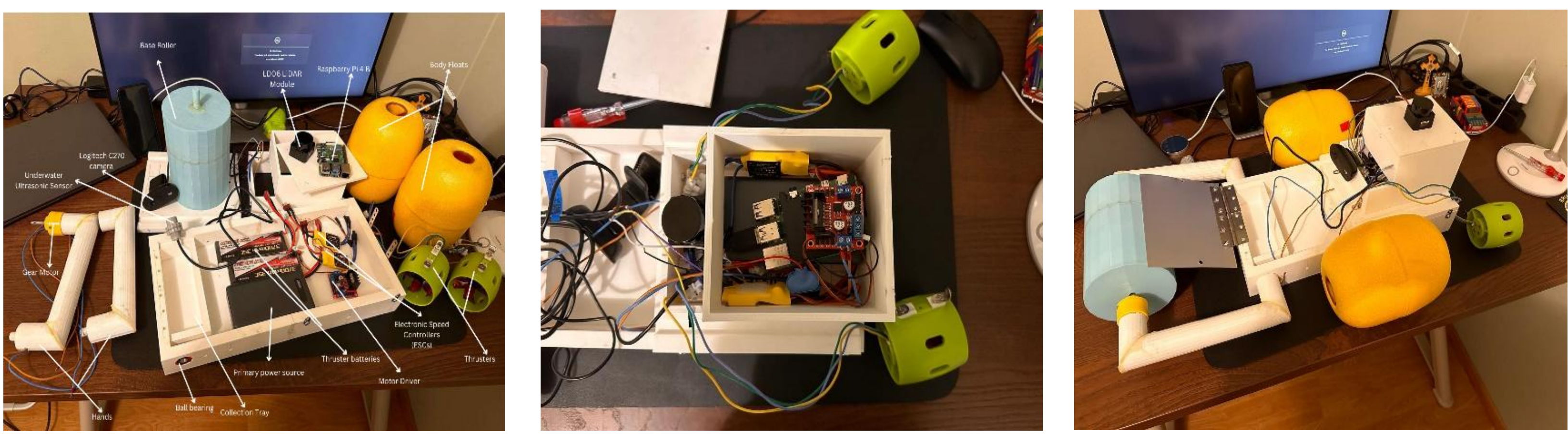


Image 1: The images collectively depict the ORCA prototype, showcasing its disassembled components with annotations, internal circuitry, and fully assembled operational structure

2. Prototype

2.1. Design and assembly

ORCA's design integrates key mechanical components to ensure efficient oil collection while maintaining adaptability in diverse weather conditions. The primary structural elements include ball bearings, hinges, and a scraping mechanism that enhances operational efficiency. The hands of the skimmer, which hold the base roller responsible for carrying the plastic film, are mounted on ball bearings. This design allows the skimming mechanism to dynamically adjust to wave motion, ensuring that oil collection remains uninterrupted even in turbulent waters. The ball bearings further enhance this adaptability by allowing a full range of motion, minimizing mechanical resistance, and ensuring a smooth, responsive movement of the skimming hands.

To enhance oil recovery efficiency, the skimmer incorporates an aluminum scraper positioned at a fixed angle. This scraper is attached using hinges, ensuring that it remains in optimal contact with the plastic film as oil is removed. The ability of the scraper to move in conjunction with the skimming mechanism prevents excessive stress on the system while maintaining consistent separation of oil from the film.

The structural framework of the skimmer is predominantly hollow, reducing overall weight while ensuring sufficient buoyancy. This lightweight design minimizes energy expenditure and allows the device to operate with greater hydrodynamic efficiency. Additionally, the weight distribution has been carefully optimized: the heavier skimming components, including the roller and scraper, are positioned at the front to facilitate submersion and effective oil collection. In contrast, the motors and power sources (batteries) are placed at the rear, counterbalancing the system to maintain overall stability. This arrangement prevents forward tilting and ensures uniform contact with the oil layer.

To enhance durability and functionality in real-world conditions, all electronic and mechanical components are enclosed using fiberglass tape. This provides essential waterproofing and electrical insulation, protecting critical circuitry such as the Raspberry Pi, motor controllers, and primary power source from exposure to water and oil contaminants. These protective measures ensure long-term operational reliability, making the skimmer suitable for deployment in oil spill environments.

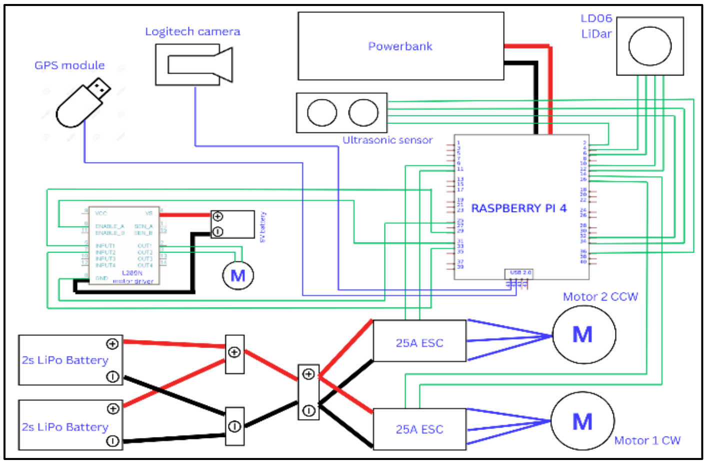


Figure 1: Real time diagram of the complete electrical assembly in ORCA

Figure 1 illustrates the circuit schematic which shows how all the components and sensors feed data to the Raspberry Pi. the Raspberry Pi processes these inputs and sends signals back for movement, navigation, and skimming processes. The connections include power (red/black), control signals (green), and data (blue).

2.2. Obstacle Avoidance

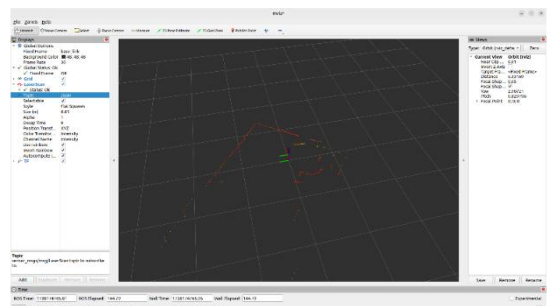


Image 2: Real-Time LiDAR Mapping Capturing Environmental Layout for Autonomous Navigation

Efficient obstacle avoidance is an important feature in this autonomous oil skimmer, ensuring uninterrupted operation while preventing collisions with floating debris, boats, or other obstacles. The system achieves this using a combination of LiDAR and ultrasonic sensors with all data processed by a Raspberry Pi to enable real time navigation. The LiDAR scans the surrounding environment in 360 degrees and provides precise distance measurements, upto 12 metre and detects both stationary and moving objects creating a real time 2D map.

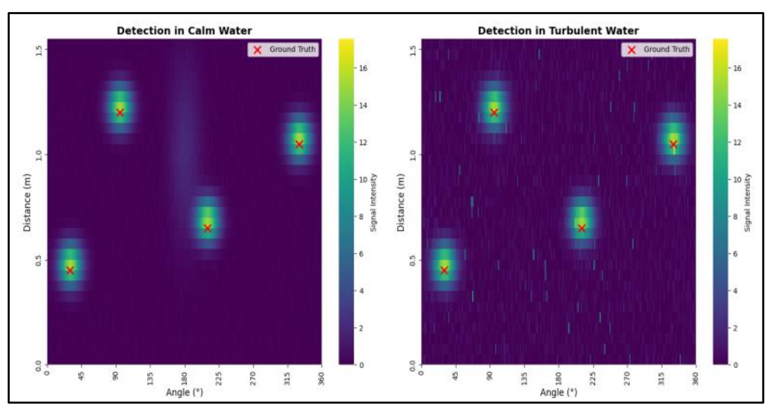
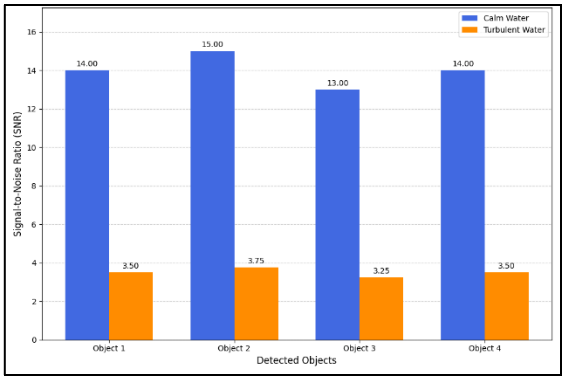


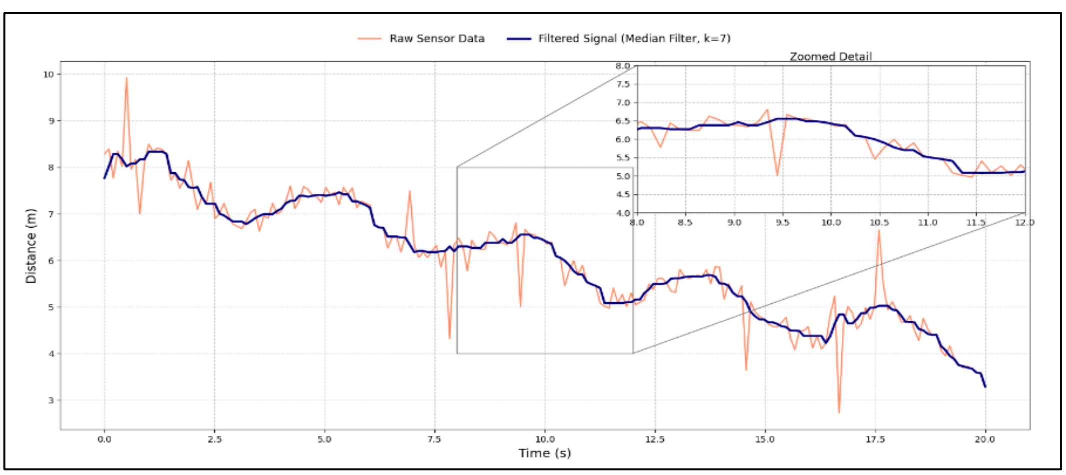
Figure 2: Comparison of Target Detection Accuracy in Calm vs. Turbulent Water Conditions Using LiDAR Signal Intensity

To validate the LiDAR performance, we conducted a controlled experiment where four objects were fixed at a known distance and angle from the LiDAR sensor which was defined as the “ground truth.” We then performed two scans under different real world water conditions for an oil skimmer: calm water and turbulent water. The raw data from these scans was processed to generate detection heatmaps, represented by *Figure 2*. As seen in the “detection in calm water” map, the sensor gives a clean output with four distinct high intensity signals aligned with the ground truth locations of the objects. However the “detection in turbulent water” map shows background noise caused by the reflections of the choppy water surface, but despite the noise the system does identity the four primary object. To quantify this difference in signal quality, the Signal to Noise Ratio (SNR) was calculated for each detection, which is the measure of measure of the object’s signal strength relative to background noise. The signal is defined by the highest intensity of the object and the noise is the standard deviation of the background intensity across the map. As shown in *Graph 1*, the calm water has high SNRs between 13.00 and 15.00 which means it has clean and reliable signals, whereas in turbulent water, the SNR drops significantly to a range of 3.25 to 3.75, showing the impact of water turbulence on the LiDAR.



Graph 1: Comparison of Signal to Noise Ratio in two different simulations.

The ultrasonic sensor is the secondary short range detection system primarily for obstacles closer than 4 metre. It is used to confirm the obstacles identified by LiDAR and detect objects that may not be signaled by LiDAR such as low floating debris.



Graph 2: Comparison of Raw vs. Filtered sensor data

A significant challenge with ultrasonic sensors is signal noise caused by water splashes which can result in unreliable distance readings. To ensure reliable data, the raw data from the sensor is processed using an algorithm to filter it. *Graph 2* provides the comparison between the raw sensor output and the filtered data. The raw data has frequent sharp spikes that are not representing of the actual distance to an object. To avoid this, a median filter is applied which analyses the data points and selects the median value as the true output of the sensor. As shown in the zoomed in part, this method is effective in rejecting the outliers spikes while preserving the trend of the data, providing smooth and stable navigation system.

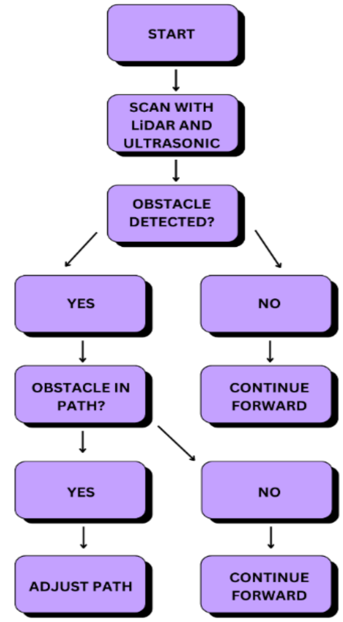
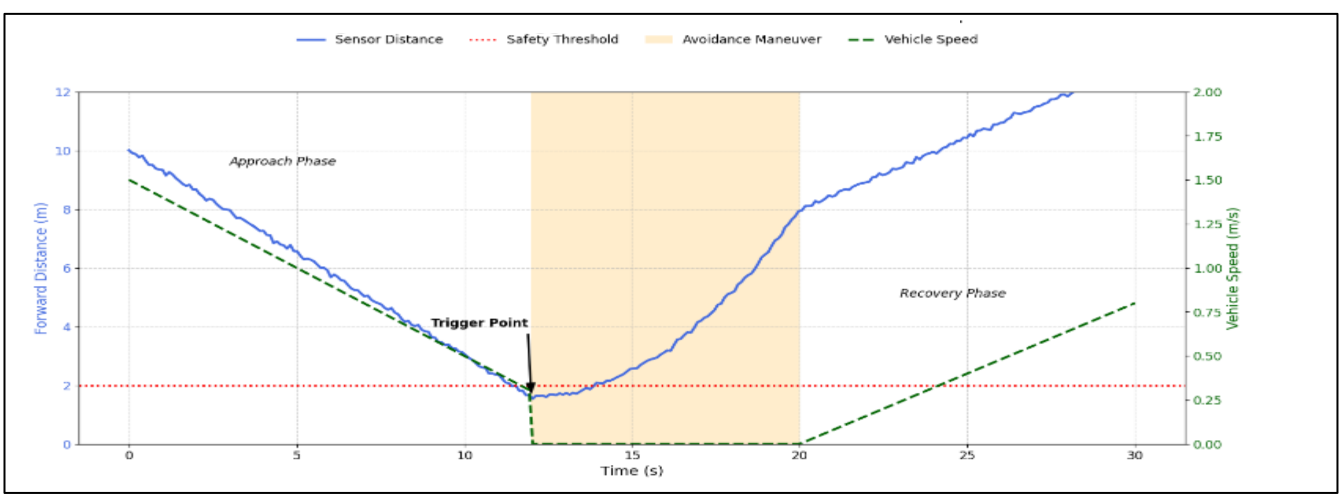


Figure 3: Flowchart Representation of the Obstacle Avoidance System Processing Sensor Data for Path Adjustment

This data is then used to execute the skimmer obstacle avoidance logic which is shown in the flowchart. The Raspberry Pi processes data from the GPIO signals from both sensors and determines the necessary maneuvers to avoid obstacles without deviating from the oil collection path. When an obstacle is detected, the system calculates the maneuver required to bypass the obstacles and maintain route.

- If the obstacle is detected on the right, the skimmer adjusts leftward by increasing speed on the right motor, and decreasing speed on the left.
- If the obstacle is detected on the left, the skimmer adjusts rightward in a similar way.
- If it cannot adjust path, then the skimmer stops and reverses before recalculating an alternate path.



Graph 3: A complete Sensor-Triggered Obstacle Avoidance Maneuver

Graph 3 quantifies our algorithm's avoidance maneuver in a graphical representation.

Approach phase: the vehicle is moving toward an obstacle and the sensor distance steadily decreases.

Trigger point: the system has a defined safety threshold at 2 meters. The moment the sensor distance crosses this threshold, the avoidance maneuver begins.

Avoidance maneuver: this is highlighted by the shaded region, which when triggered causes the vehicle speed to reduce to zero stopping the skimmer's forward motion. The system then executes a turn or a reverse causing the sensor distance to increase as the skimmer moves away from the obstacle.

Recovery phase: once the skimmer has navigated to a safe distance, the avoidance maneuver ends and the vehicle begins to accelerate again, and continuing its operational path.

2.3. Oil Detection and Collection

An AI model was trained using a dataset of 800+ images from public datasets similar to the environment where the oil skimmer operates, including both oil covered and oil free water surfaces. These images were individually annotated with bounding boxes to label areas with oil up to 2.1 annotations per image.

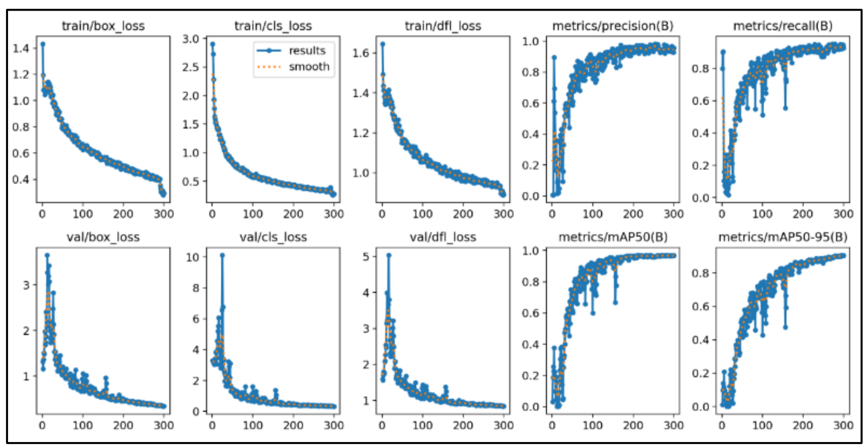


Figure 4: Training Performance Graphs of AI Model for Oil Detection on Water

The training graphs shown in *Figure 4* visualise the AI model's performance in detecting oil on water over 300 epochs. The loss function graphs – box loss, classification loss(cls_loss), and distribution focal loss(dfl_loss) – show a consistent downward trend, indicating effective model learning. Box_loss exhibits improvements in bounding boxes accuracy, cls_loss shows improved object classification over time, and dfl_loss steadily decreases refining the precision of bounding box localization. The validation loss graphs follow a similar pattern, confirming that the model generalizes well to unseen data. Additionally, the precision and recall graphs show an increasing trend, approaching 1.0, indicating high detection accuracy with minimal false positives and negatives. The mean average precision (mAP) graphs (mAP50 and Map50-95), stabilize around 0.9-1.0, demonstrating reliable detection across various IoU thresholds. These trends overall confirm an effectively trained, high performance model with 97% precision capable of accurate oil detection and localizing oil spills.

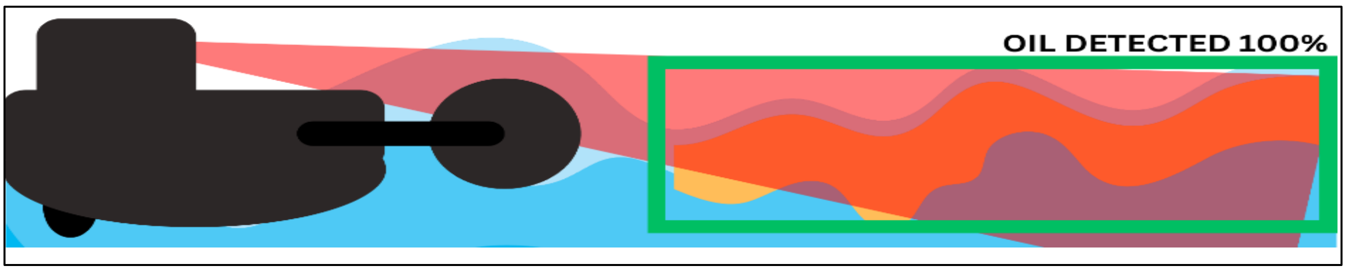


Figure 5: This image represents the initial concept of our oil detection system, illustrating how the AI-powered skimmer would scan the water surface and identify oil spills within a defined detection region.

The oil skimmer prototypes uses a Logitech C270 camera (720p, 30FPS, 60° FOV) mounted at a 45° downward angle to detect oil on the water surface. The camera feeds into the Raspberry Pi which processes the live video using the AI model. When detecting oil, the AI sends a GPIO signal to activate the control system which consists of a L298N motor driver and delivers a maximum of 9V, 1.5A to a DC motor rotating at 80-100 RPM. The DC motor rotates the oil skimmer roller made from polypropylene with a 1mm silicone coating to improve oleophilicity . The roller operates only when oil is detected, optimizing energy usage. Oil stuck to the roller is scrapped using a 3mm aluminum sheet fixed at a 30° angle relative to the roller which then flows into a 3x5x14 cm collection container. The entire system is automated with AI detection ensuring a response time of less than 3 seconds from oil detection to the motor activation.

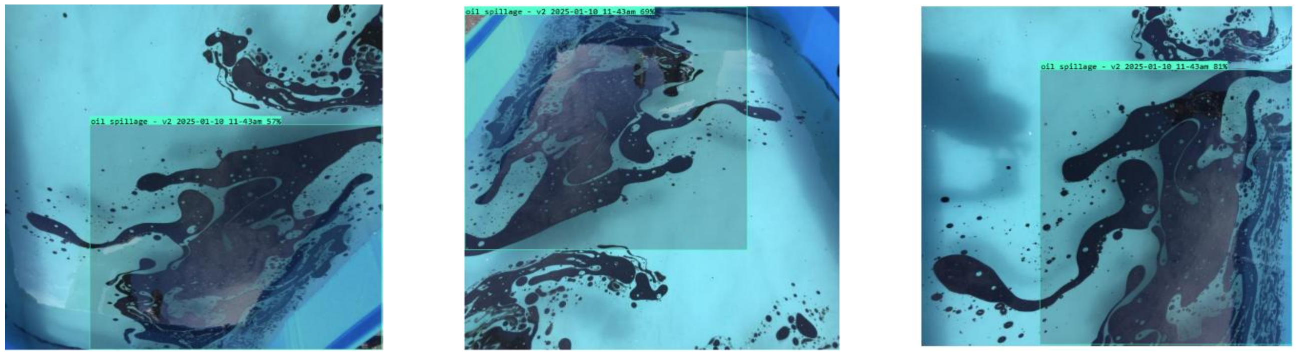


Image 2: These real-time images show the AI model accurately detecting oil spills on water surfaces, highlighting the effectiveness of the trained detection system in practical applications.

2.4. Polypropylene with Silicone Coating for Oil Spill Remediation

We chose polypropylene (PP) with a silicone spray coating for this study because of its well-defined molecular properties, surface energy characteristics, and interactions with oil and water. The efficiency of an oil skimmer depends on its ability to selectively attract oil while repelling water, ensuring effective oil recovery in marine environments. By examining the fundamental chemical and physical properties of this material, its suitability for oil spill remediation can be scientifically justified.

Polypropylene is a nonpolar hydrocarbon-based polymer composed of long chains of covalently bonded carbon and hydrogen atoms. Its molecular structure lacks functional groups that engage in polar interactions, as in hydrogen bonds, making it inherently hydrophobic. Such exhibitions are noticed when water molecules, which exhibit strong intermolecular hydrogen bonding, do not interact favourably with nonpolar surfaces, leading to high water contact angles. In contrast, petroleum fractions, primarily composed of hydrocarbons, interact with polypropylene through weak London dispersion forces, allowing it to stick effectively. Polypropylene, which differs from other similar materials by the presence of a methyl (-CH_3) group on alternating carbon atoms, exhibits even lower surface energy, further reducing water adhesion while enhancing attraction for oil. The wetting behaviours of this material can be understood in terms of surface energy. Water, has a high surface tension of approximately 72 mN/m, and

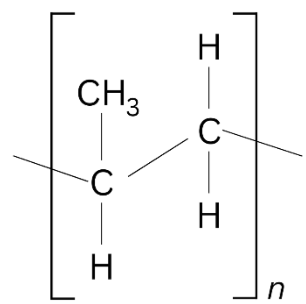


Figure 6: Polypropylene chemical structure.

does not spread easily on low-energy surfaces such as polypropylene (29–31 mN/m), resulting in water repulsion. On the contrary, oils with lower surface tension (~20–30 mN/m) readily spread across these polymer surfaces, ensuring strong adhesion. This difference in free energy between oil and water enables selective oil absorption while minimizing water contamination. These properties make polypropylene highly effective for oil separation.

To further enhance these properties, a silicone spray coating is applied to the polymer surface. Silicones, composed of a chemically inert siloxane (Si-O-Si) backbone, are highly hydrophobic and possess an exceptionally low surface energy (~20–25 mN/m). This coating increases water repellence while maintaining strong interactions with hydrocarbon-based oils. Additionally, the thin film of silicone enhances oil retention by creating a tacky, oleophilic surface, improving efficiency in oil recovery, particularly for higher viscosity spills. Furthermore, silicone coatings provide durability, protecting the polymer from environmental degradation and ensuring sustained performance over extended operational periods.

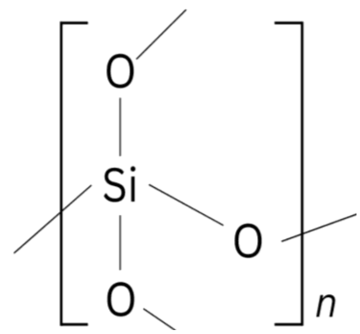


Figure 7: Silicon Polymer Structure

The combined properties of polypropylene, further improved through silicone treatment, make it an ideal material for oil spill remediation. Its low surface energy, nonpolar nature, and high oil attraction allow oil capture while repelling water, optimizing skimming efficiency. The addition of a silicone layer further enhances these attributes, increasing durability and separation performance. These factors make the material highly suitable for integration into our prototype, ensuring effective oil recovery in diverse spill conditions.

3. Testing and Experimentation

We are conducting this experiment to validate our oil skimmer's effectiveness in real-world conditions, ensuring it performs as intended in practical applications. The key objectives are to assess its ability to efficiently separate oil from water, measure its hydrophobicity, and evaluate its oleophilicity. By replicating real spill scenarios, we can assess the skimmer's design, optimize its material properties, and confirm its efficiency before deployment. This testing phase is crucial to ensure that our solution is not only theoretically sound but also practical, reliable, and scalable for real-world oil spill remediation.

Image 3: Prototype Oil Skimmer in Action: Testing Oil Removal Efficiency in a Controlled Setup

3.1. Variables

The independent variable is the viscosity of oil, measured in centipoise (cP). Five oils were selected based on their viscosity as room temperature to ensure precision

	Commercial Product	**Type of oil**	**Viscosity (cP) {AT 25° Celsius}**
1	Baby oil	Light oil	65
2	Light Motor oil (SAE30)	Intermediate oil	128
3	Mineral oil	Intermediate oil	199
4	Castor oil	Heavy oil	371
5	Motor oil (SAE 90)	Heavy oil	500 -800

Table 1: Selected Oils and Their Viscosity Levels for Experimental Testing

These represent a range from low to high viscosity, reflecting real-world spill conditions. Viscosity is manipulated by varying oil types while keeping external factors stable.

The dependent variable is skimming efficiency, measured as a percentage. The modified PP sheet is attached to the skimmer and tested in a tank containing 150 mL of oil atop water. The collected solution is assessed against the following formulas to find the overall efficiency of our prototype:

- Skimming Efficiency(%) = (Oil Collected (mL) / Initial Oil (mL)) ×100
- Water Rejection Efficiency(%) = (Oil Collected (mL) / Total liquid collected(mL)) ×100

Control Variables: The external temperature is maintained at 25°C to prevent viscosity variations. The oil volume is consistently measured at 150 mL to ensure comparability. The skimming duration is precisely controlled at 5 minutes using a stopwatch.

3.2. Methodology

Polypropylene sheets (38 cm ×17 cm) are evenly coated with silicone spray. Five oil samples are prepared, each measured precisely. The oil is poured onto water and allowed to settle before the skimmer is activated. After 5 minutes, the oil collected is separated using a pipette and measured in a measuring cylinder. The procedure is repeated thrice per oil type to ensure reliable data. The PP sheet is replaced after each trial to prevent contamination.

The volume of oil collected will be recorded systematically. Higher viscosity oils retain more water, affecting efficiency. By systematically varying oil viscosity, the experiment evaluates how skimming efficiency changes under controlled conditions, ensuring precise and reproducible results.

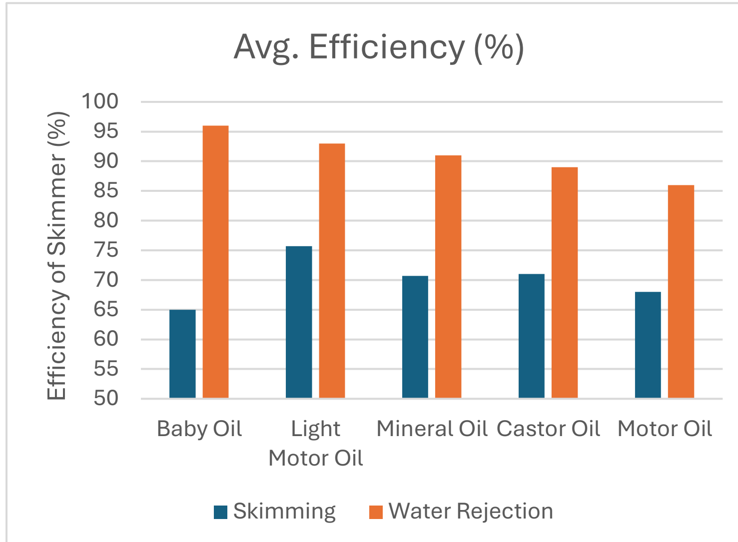
3.3. Results

Type of oil	Oil Collected (mL)			Water Collected (ml)			Avg. Water Rejection Efficiency (%)	Avg. Skimming Efficiency (%)
	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3		
Baby oil	99.0	96.0	102.0	5.0	4.5	5.5	96	65.0
Light Motor oil	114.0	111.0	120.0	7.0	6.5	7.5	93	75.7
Mineral oil	108.0	102.0	111.0	10.5	10.0	11.5	91	70.7
Castor oil	102.0	111.0	105.0	14.5	13.5	15.0	89	71.0
Motor oil	96.0	105.0	99.0	17.0	16.0	18.5	86	68.0

Table 2: Skimming Performance and Water Rejection Efficiency Across Different Oil Types.

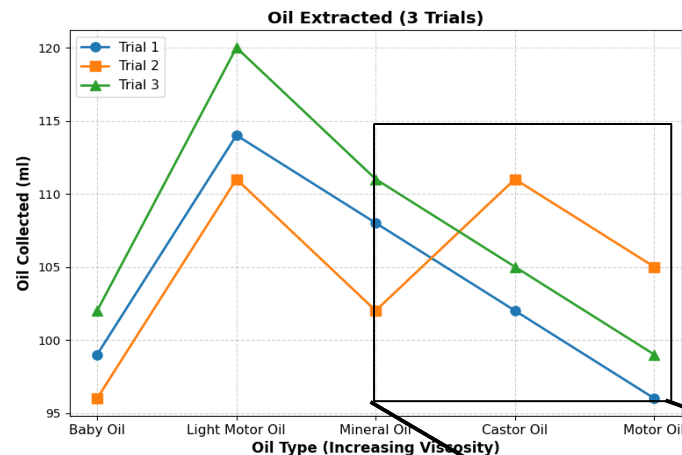
3.4. Discussion

The experimental evaluation of silicone-treated polypropylene (PP) sheets for oil skimming efficiency provided insights into the relationship between oil viscosity, material performance, and external environmental factors affecting oil recovery. The efficiency of oil removal was tested over three trials for each material, with new PP sheets introduced for each trial to prevent efficiency carryover between tests. The results indicated clear efficiency trends, with moderate-viscosity oils exhibiting the highest recovery rates, while both low-viscosity and high-viscosity oils presented distinct skimming challenges. Additionally, experimental inconsistencies, environmental influences, and mechanical factors played a significant role in efficiency variability, particularly in the case of oil displacement caused by skimmer-induced turbulence.



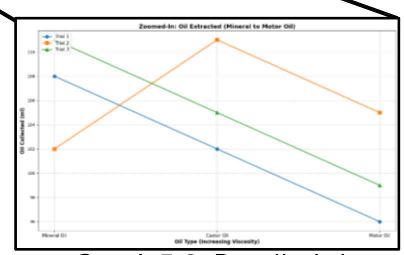
Graph 4: The average skimming and Water Rejection Efficiency of ORCA against increasing viscosities of oils.

An analysis of Polypropylene performance visualised in *Graph 4* demonstrates that PP consistently exhibited higher skimming efficiency for moderate- and high-viscosity oils. The overall efficiency values ranged between 65.0% and 75.7%, with Light Motor Oil yielding the highest skimming efficiency (75.7%), likely due to its optimal balance between viscosity and molecular adhesion properties. Mineral Oil followed closely at 70.7%, while Castor Oil exhibited the highest efficiency among high-viscosity oils (71.0%). Conversely, Baby Oil exhibited the lowest efficiency (65.0%), which can be attributed to its low surface tension and rapid dispersibility, leading to increased resistance to skimmer adhesion. Motor Oil, a highly viscous substance, showed a moderate efficiency of 68.0%. Each trial used a completely new PP sheet to ensure consistency and prevent efficiency carryover from previous trials. However, in Trial 2, the PP sheet ruptured during skimming of Castor Oil and Motor Oil, requiring mid-experiment replacement with a fresh film, which may have introduced variability within that specific trial. After replacing the PP sheet, the experiment resumed from the exact point at which it had been interrupted, with the skimmer continuing its operation in Castor Oil. Unexpectedly, Castor Oil's skimming efficiency surpassed that of Light Motor Oil and Mineral Oil (71.0% compared to 70.7%) as depicted by the orange line in graph 5.2, despite the latter two being lower-viscosity oils that should have exhibited stronger adhesion to the PP surface. This anomaly suggests that the silicone coating may degrade over time, reducing the material's oleophilic efficiency with continued use. While this degradation did not significantly impact the results within the limited scope of this experiment, it raises concerns regarding long-term operational efficiency in real-world oil spill scenarios.



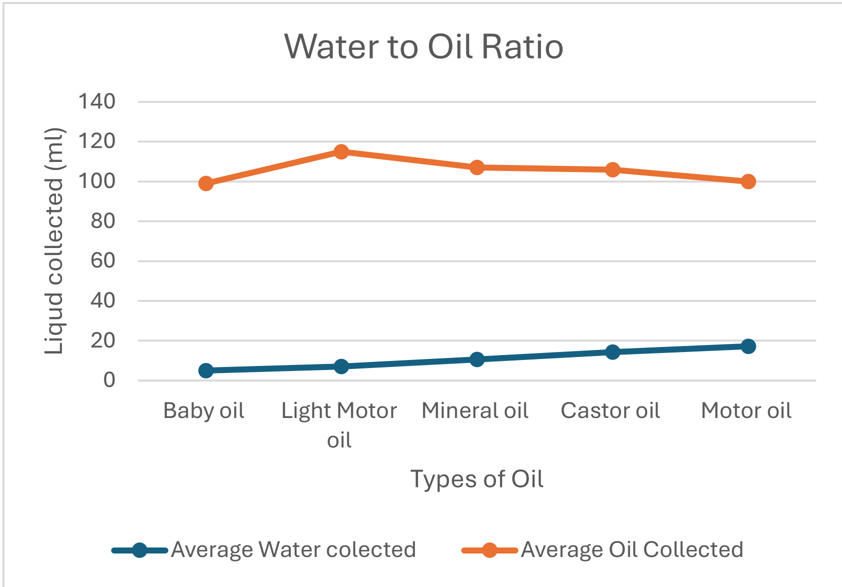
Graph 5.1: Oil Extracted Across 3 different Trials against different viscosities of oils.

An important addition to this analysis is the measurement of water rejection efficiency, which determines the amount of water retained during skimming. As illustrated in graph 3, the results show that water retention increases as viscosity increases, suggesting that higher-viscosity oils tend to trap more water. Baby Oil demonstrated the highest water rejection efficiency at 96%, with an average of 5 mL of water collected per trial, while Motor Oil, being the most viscous, had the lowest water rejection efficiency at 86% and retained an average of 17.2 mL of water per trial. This trend highlights the trade-off between oil skimming efficiency and water rejection, as more viscous oils exhibit better adherence to the PP surface but also retain more water, which may impact oil recovery purity. This finding suggests the necessity of refining material selection or incorporating a secondary water separation mechanism in large-scale oil recovery efforts.



Graph 5.2: Detailed view of Trial 2 after the silicone enhancement.

The influence of oil dynamics within the testing environment introduced additional experimental challenges that affected skimming performance. Oil displacement due to the rotational motion of the skimmer was observed, particularly for low-viscosity oils, which exhibited a tendency to be repelled rather than collected. This effect was especially evident for Baby Oil, which demonstrated poor adhesion to the skimming surface due to its low molecular cohesion and high mobility on the water surface. The turbulence generated by the skimmer's motion resulted in oil redistribution toward the edges of the container, reducing its accessibility to the skimming mechanism. This observation suggests that fluid turbulence and surface flow dynamics play a crucial role in determining oil retention efficiency, emphasizing the need for optimization of the skimmer's intake mechanism to reduce oil displacement, particularly for low-viscosity hydrocarbons.



Graph 6: The volume of water collected in comparison to the volume of oil collected against different viscosities of oils

Overall, the results demonstrate that silicone-treated PP films exhibit strong potential for oil spill remediation, though further optimizations are required to enhance their efficiency under variable conditions. The observed repulsion of low-viscosity oils due to mechanical turbulence suggests the need for modifications in the skimmer's hydrodynamic design. Additionally, while the silicone coating effectively enhanced oil adhesion, the study highlights the importance of evaluating its long-term durability under continuous exposure.

4. Future Goals

4.1. ORCA 2.0

Building on the foundation set by the initial prototype, ORCA 2.0. introduces a variety of upgrades to overcome the earlier limitations in buoyancy, balance, electronics integration, and oil skimming efficiency.

A key advancement is the introduction of a crane based skimming mechanism which replaces the fixed hands of the previous model. In the earlier version, the hands were in constant contact with the water which caused drag, imbalance, and partial submersion. ORCA 2.0. solves this by having retractable crane arms that keeps the skimming hands elevated during navigation, and only lowering them during the oil collection process. This enhances energy efficiency and stability in dynamic water conditions.

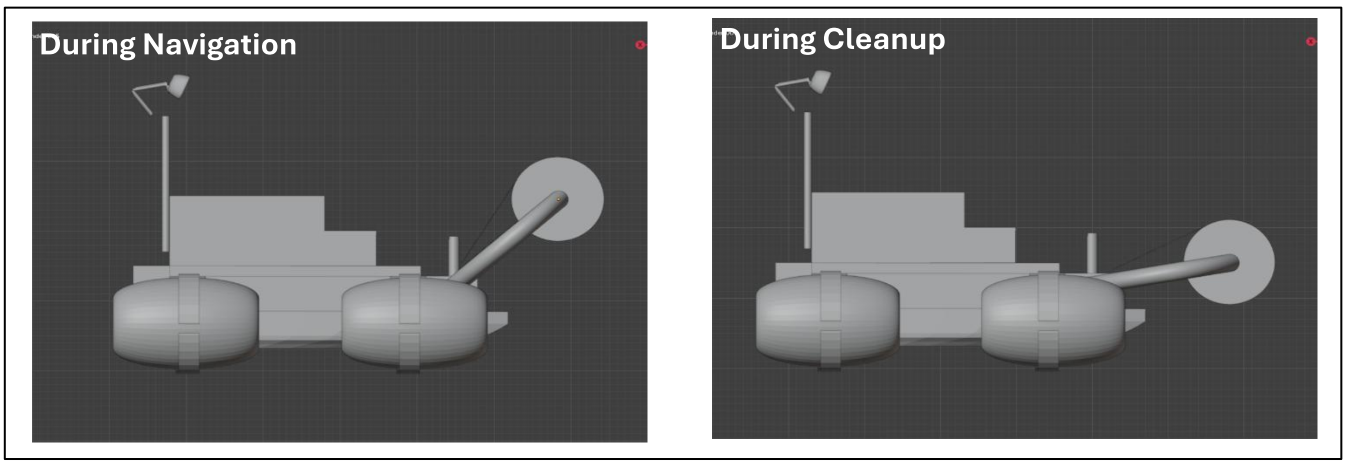


Image 4: Side View of ORCA 2.0's Retractable Crane-Based Skimming Mechanism in Raised and Deployed Positions

The hull is designed using a catamaran style structure which significantly improves buoyancy and stability. This twin hull configuration increases the surface area, reduces water resistance, and improves balance in rough conditions. In addition, angled floatation arms were added to support

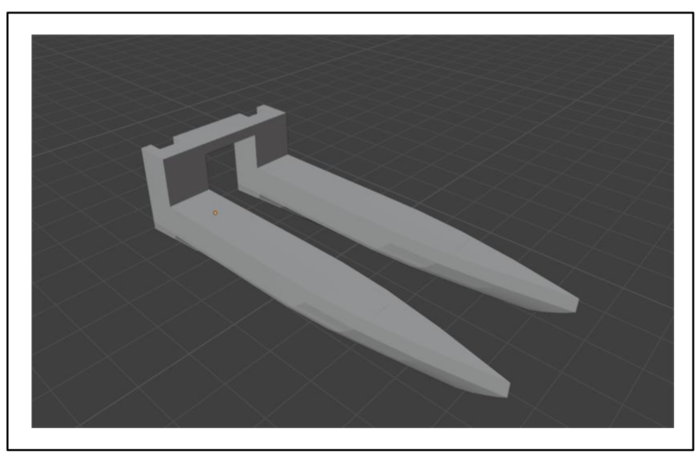


Image 5: Hull design for ORCA 2.0, inspired by catamaran boats

horizontal stability and minimized tilting caused by waves. The motors also have been repositioned within the hull to improve weight distribution and reduce drag, resulting in smooth propulsion and more precise control over maneuvers.

To support additional functions, the electronics compartment has been expanded, which allows better waterproofing, airflow, and organization of components. This allows more components to be fitted such as a water quality sensor, which gives live readings of environmental parameters like pH, turbidity, and temperature, improving the system's capabilities during oil spill responses. Further ecological considerations led to addition of underwater acoustic deterrents which emit safe targeted frequencies to guide the marine life away from contaminated zones to reduce ecological disturbance and keep them safe during cleanup processes.

Designed with keeping in mind the future adaptations, ORCA 2.0. subtly supports modular systems and a coordinated swarm system, which will be talked about in following sections. These improvements make ORCA 2.0. a smarter, more stable, and environmentally responsive prototype for autonomous oil spill remediation.

4.2. Multipurpose Module

To make ORCA as economically feasible and operational as possible, we hope to make it into a multipurpose module – a same fitting method for the arms interface. This all in one approach will allow fast swapping of mission specific attachments, whether it for oil skimmers and water quality testing or debris collectors and bioremediation units. Because its sharing of same power, navigation, and communication system across the different modules, the production costs drop and each ORCA prototype can be tailored on the spot to fit the type of pollution it is remedying.

For example, there are limitations of our current roller scraper design in colder temperatures where oil viscosities increase and resist adhesion. We are working on developing a suction driven skimming head. The system will rely on a controllable vacuum and replaceable oleophilic filters to collect in oil without relying on adhesion. The intake point of the vacuum can be adjusted in height and angle using the existing crane arm mechanism which ensuring consistent contact and collection when oils forms a slushy solid consistency.

We aim beyond hydrocarbons, the multipurpose module concept extends ORCA's capabilities to a variety of aquatic threats. Current prototyping ideas under development include:

Algal bloom extractor: a mesh conveyor belt system that lifts and removes the water and stores the harmful algae on board for disposal or processing.

Microplastics harvester: a targeted intake system that filters surface water through fine meshes and electrostatic plates to trap suspended microplastics. Captured particles are stored in onboard cartridges, with adjustable control and track plastic-rich areas effectively.

By combining all these capabilities on a common platform, makes ORCA a truly adaptable, cost effective environmental response solution, one where a single unmanned aquatic rover can transition between oil spills, harmful algal blooms, and plastic pollution in minimal times.

4.3. Swarm System

One of our main goals for the future is the development of a swarm based system that is centred around a mothership and a fleet of autonomous ORCA skimmers. The mothership will serve as a the command centre and data processing for the entire operation. It will be responsible for controlling the movements of the ORCA units, processing the collective data they gather, and creating a communication link between all the units.

The mothership will be equipped with solar panels, which allows it to act as a sustainable on water charging station for the units. This ensures longer operational time for the entire fleet, allowing continuous clean up missions over consecutive days without the need to return to land for external power sources.

In this system, multiple ORCA skimmers will work in collaboration. With the help of AI, they will share real time data on oil spill characters, location, and amount sources from their sensors and potentially assisted by external intelligence from technologies such as satellite imaging or a drone based aerial surveillance through the mothership. This constant data exchange allows for intelligent task allocation managed by the mothership and potentially supported by decentralized AI communication between individual ORCAs for localised responsive adjustments.

This approach will dramatically increase clean up efficiency, reduce operational redundancy, and allow for faster response times especially in larger scale spill scenarios. By intelligently distributing the ORCA units across a spill, the system can adapt dynamically to changing conditions which allows optimal coverage of the spill and utilization of resources. The goal of this system is to achieve a fully autonomous, highly efficiency, and environmentally conscious oil spill remediation system capable of large scale, sustainable deployment for the protection of marine ecosystems worldwide.

5. Conclusion

This project successfully demonstrated the feasibility and effectiveness of the ORCA system as the next generation solution for oil spill remediations. With the use of AI, advanced navigation systems, optimized material science, the ORCA prototype can operate autonomously, overcoming the limitations of traditional cleanup methods that are inefficient, environmentally harmful, and dangerous to human workers.

The integration of intelligent detection of oil spills, autonomous navigation, and optimized materials proved validated our model's efficiency. Our model has a 97% precision in detecting oil and triggering the collection process in under three seconds. The navigation system with LiDAR and ultrasonic sensor with data filtering, has reliable obstacle avoidance even in turbulent waters. the silicone coated polypropylene material showed high skimming efficiency (65.0-75.7%) and excellent water rejection (up to 96%) proving its efficiency in various oil viscosities.

The study has identified areas for improvements such as reduced LiDAR performance in turbulent conditions and potential degradation of the oleophilic coating. These understanding pave a path for future developments and upgraders rather than hinder the progress. Automating this cleanup removes human risk by keeping workers away from toxic environments

The plan for ORCA 2.0., multipurpose modules, and the swarm technology highlight a scalable, adaptable environmental response system. in conclusion, ORCA is proven to be more than a prototype - it represents a foundational step towards a smarter, safer, and more sustainable marine cleanup remediation, proving that AI and autonomous systems will change the way we protect our oceans.

6. References

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