Chapter 2: System Design

1. Mechanical Desgin

1.1 Introduction

The mechanical concept at the core of this project is focused on designing an autonomous boat with exceptional stability, efficient movement, and reliable waste collection capability. Each design decision aims to fulfill the essential requirements: maintaining steady buoyancy, enabling smooth navigation, and securely supporting the waste collection net and associated systems.

A defining choice in the mechanical design is the adoption of a catamaran (twin-hull) structure. Catamarans are widely recognized for their superior stability compared to single-hull (monohull) boats. This is primarily due to their broader beam and dual hulls, which distribute buoyancy over a larger area, greatly reducing rolling and pitching. Such characteristics are especially beneficial when weight distribution becomes uneven, for instance, as the collection net at the stern fills with debris. The inherent stability of catamarans decreases the risk of capsizing and ensures predictable movement, even under varying load conditions.

These advantages are well-documented in naval engineering literature. Carlton (2018) notes that the wide stance of a catamaran provides high initial stability, making it less prone to rolling from shifting loads or waves [1]. Molland et al. (2011) further emphasize that twin-hull vessels maintain consistent trim and are ideal for applications requiring a stable working platform, such as waste collection [2]. Experimental studies and simulations also demonstrate that catamarans can safely carry heavier or unevenly distributed loads, a critical factor for autonomous operation [3].

The waste collection net is purposefully positioned at the stern, facilitating unobstructed debris collection while keeping clear of propulsion and navigation mechanisms. The rear structure is reinforced to bear the added stress from the net and collected waste, ensuring overall balance and operational dependability.

Why choose a catamaran design?

- Superior stability: Twin hulls distribute weight evenly and help the vessel remain upright, even in rough or unevenly loaded conditions.
- Smoother navigation: Reduced hydrodynamic resistance and minimized rolling and pitching support efficient, predictable movement.
- Greater load capacity: The wide stance enables the boat to safely carry substantial loads, such as a full net, without compromising stability.

1.2 Boat Model Overview

To illustrate the overall design and arrangement of the autonomous waste-collecting boat, Figure 1.2 presents a 3D model of the complete system. This model highlights the main structural features, including the double-hull (catamaran) configuration, the central platform for mounting electronics and propulsion, and the dedicated area at the stern for net support and waste collection.

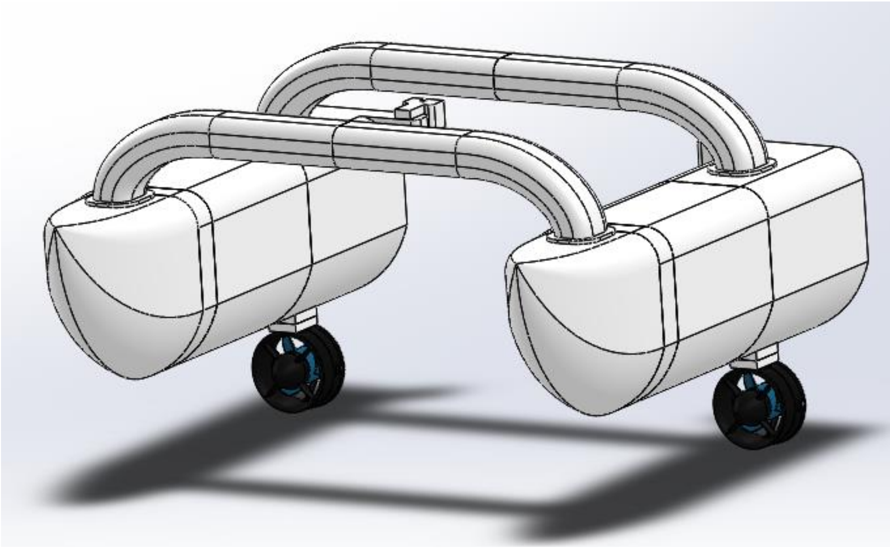


Figure 1.2 3D model of the autonomous catamaran waste-collecting boat

1.3 Structural Analysis

1.3.1 Selection Criteria for Hull Material and Thickness

The hull of the autonomous boat is constructed from ABS plastic with a wall thickness of 4 mm. ABS is widely recognized for its durability, impact resistance, and suitability for marine environments, particularly in small vessel construction [4]. According to established references, ABS hulls with thicknesses between 3 mm and 6 mm are standard for similar small-scale watercraft and provide more than adequate mechanical strength and resistance to typical operational loads [5][6]. Therefore, a detailed structural analysis of the hull's thickness is not deemed necessary for this application, as the selected material and thickness align with best practices and published engineering guidelines.

1.3.2 Bow Design

The bow (front section) of the autonomous waste-collecting boat is intentionally designed with an elliptical cross-section. This form, widely used in naval architecture, minimizes hydrodynamic drag by allowing water to flow smoothly around the vessel, reducing resistance and improving propulsion efficiency [7]. Its geometry ensures a gradual transition for water, which helps the boat move efficiently and remain stable, especially under varying loads. By following hydrostatic principles and established marine standards (such as ISO 12217-1) [8], the bow shape supports both buoyancy and balance, making it particularly suited for autonomous operation and safe waste collection.

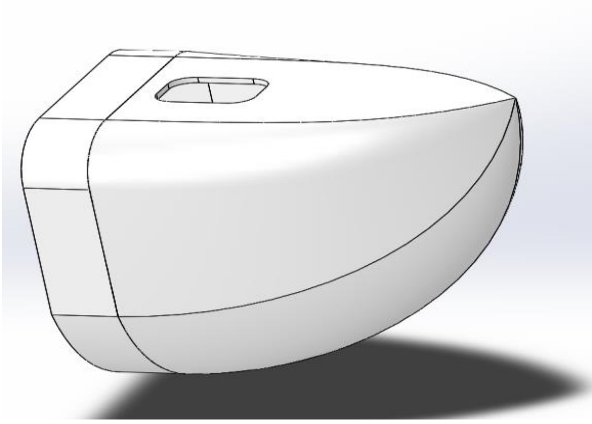


Figure 1.3.2 the front section

1.3.3 Hull Design

The hull serves as the main structural framework of the boat, dictating its overall stability, buoyancy, and performance on water. It adopts a catamaran (twin-hull) configuration, which provides superior transverse stability and reduces rolling—critical for autonomous waste collection tasks. The hull incorporates the elliptical bow described above, integrating its drag-reducing benefits at the front while providing ample volume for batteries, electronics, and propulsion systems. The use of smooth surfaces and rounded transitions throughout the hull further reduces frictional losses and complies with hydrostatic norms [2]. Weight distribution is carefully managed to preserve stability and adequate freeboard, resulting in a robust yet efficient platform for autonomous waste collection.

1.3.4 Flow Simulation Setup

Before launching the external flow simulation, it was necessary to precisely define the boat's buoyancy line (waterline), the contour where the hull meets the water at equilibrium. According to Archimedes' principle, the hull must displace a volume of water whose weight equals the total mass of the vessel. For this calculation, the total mass included both the material weight (2,161 g) and the conception load (5,136.34 g), for a combined loaded weight.

The hull's total volume, as measured from the SolidWorks 3D model, was 5,215,112.46 mm^3 (5.215 liters). Using these parameters, the equilibrium draft (vertical distance from the hull bottom to the waterline) was determined to be approximately 41 mm. This waterline was clearly visualized in the CAD model and validated by the free surface results in the flow simulation, ensuring an accurate representation of the boat's floating condition in subsequent analyses.

For the external flow simulation, the "External" analysis type was selected to study the interaction between the boat hull and the surrounding water and air. Only the outer geometry was included in the simulation by enabling the "Exclude internal space" option. A transient analysis was performed over 10 seconds, with gravity set to standard Earth conditions and the "Free Surface" option activated to realistically model the interface between water and air.

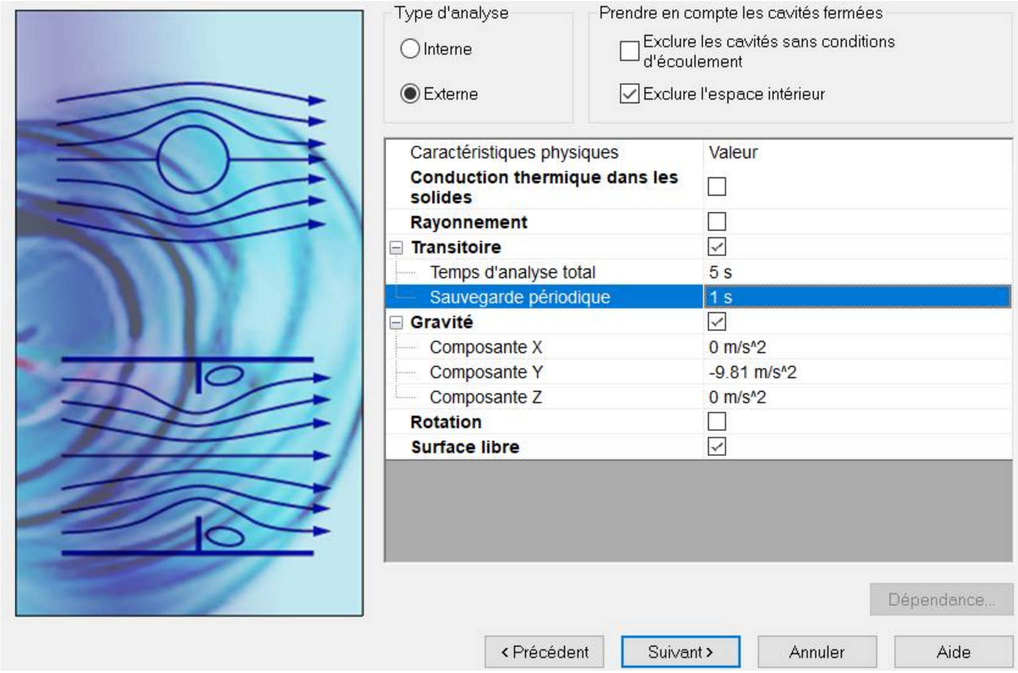


Figure 1.3.4 Flow Simulation Setup

In the flow simulation, the inlet water velocity was set to 4 knots to represent the boat operating at a relatively high speed. This setup enables the analysis of fluid behavior and resistance forces acting on the hull under dynamic conditions. After specifying the velocity, the calculation domain was defined to establish the virtual space around the boat where the simulation would be performed.

1.3.4.1 Pressure Distribution on Hulls at 4 Knots

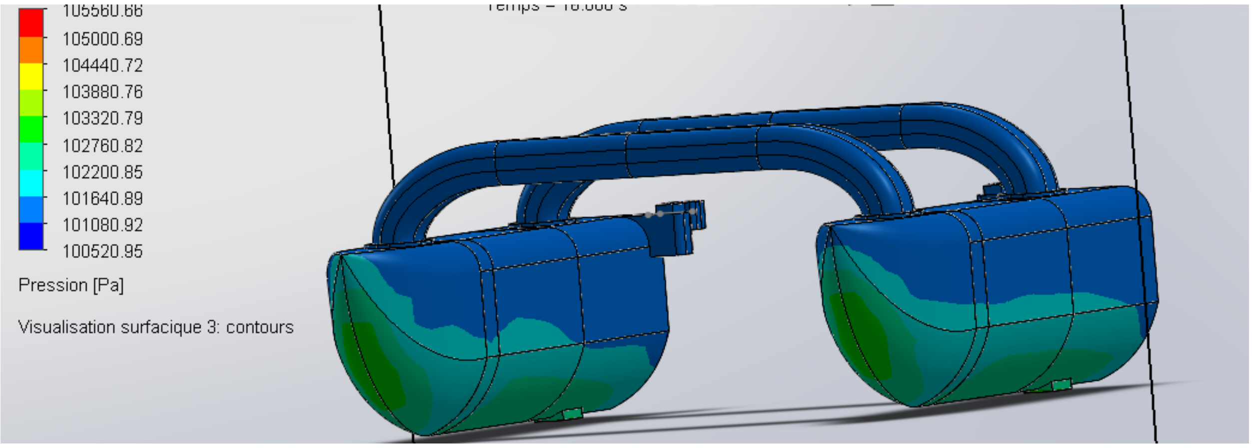


Figure 1 Pressure Distribution on Hulls at 4 Knots

This image illustrates the pressure distribution on the double-hull catamaran during the external flow simulation using SolidWorks Flow Simulation. The simulation was conducted at a velocity of **4 knots (≈2.06 m/s)** with transient analysis over 10 seconds. The color gradient indicates the pressure acting on the surface of the hulls, where:

- **Red areas** represent regions of **high pressure**,
- **Blue to green areas** indicate **lower pressure** zones.

Based on the pressure distribution shown in the image from the SolidWorks flow simulation, the dual-hull design (catamaran-style) shows balanced pressure distribution, suggesting good stability under high-speed conditions, though the peak pressure suggests potential stress points that may require reinforcement.

1.3.4.2 Velocity Distribution

The Cut Plot – Velocity from the SolidWorks Flow Simulation highlights the fluid dynamics of the dual-hull design, with velocities reaching up to 5.334 m/s near the bow and along the hull, signalling reduced pressure regions that influence drag forces. This affirms the hull’s robust hydrodynamic efficiency, enabling smooth water flow and minimized resistance, as evidenced by the simulation results.

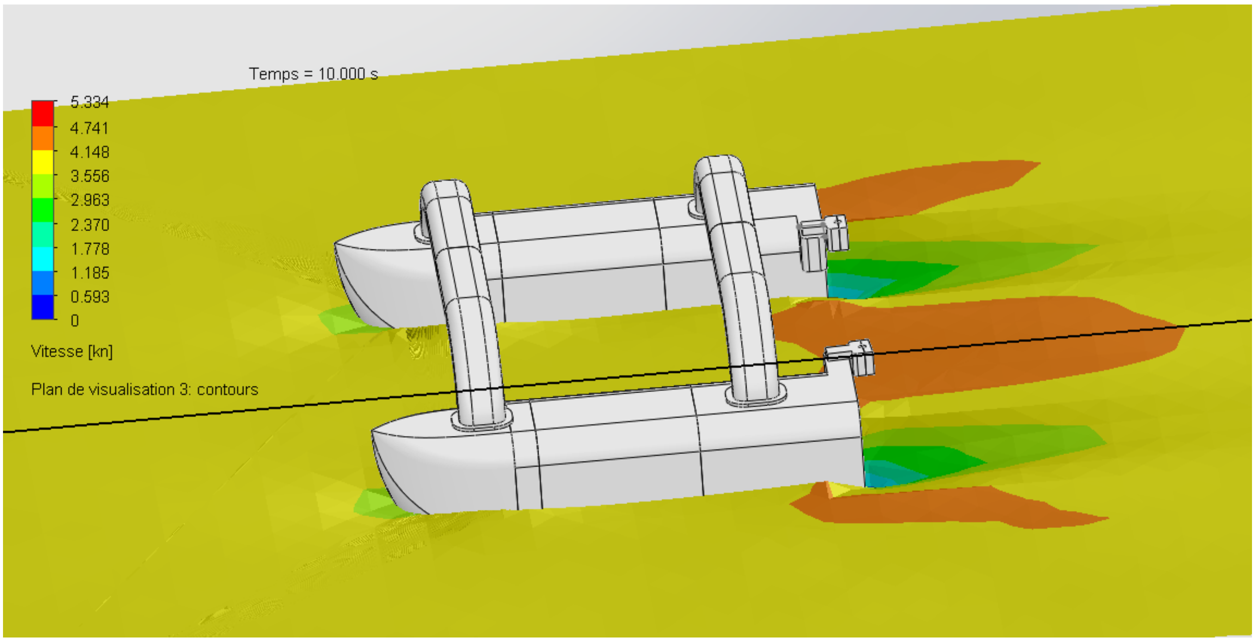


Figure 2 Cut Plot – Velocity Distribution at 10,000 s

Further analysis of the velocity distribution suggests that the higher speed zones offer potential for refinement. This Underscores the hull's effective hydrodynamic performance, promoting smooth water flow and lower resistance. However, the elevated velocity areas point to opportunities for optimization to reduce drag and improve overall movement efficiency.

2. Hardware Selection

2.1. Introduction

In any robotics project, the hardware serves as the foundation that turns innovative ideas into functional reality. For Cleaning Boat, an autonomous boat designed to collect waste in marine and lake environments, the hardware is the physical core that determines how effectively it can navigate waterways, detect debris, and execute its environmental cleanup mission. Selecting the right hardware isn't about choosing the most advanced or expensive components, it's about finding the optimal combination that aligns with Cleaning Boat's goals, balancing performance, compatibility, cost, and resilience against water and debris.

2.2. Processing unit

For *Boat Cleaning*, the processing unit must handle multiple critical tasks: running the Robot Operating System (ROS Noetic) for seamless component integration, executing an AI model for real-time waste detection from camera images, processing sensor data for navigation, and controlling motors for propulsion. To optimize performance and distribute workloads, we propose a dual-microcontroller architecture. The primary microcontroller will manage ROS, the AI model, and high-level processing, while a secondary microcontroller will handle GPS data processing and motor control, ensuring efficient task separation and system reliability.

2.2.1 Microcomputer Selection

The primary microcomputer must offer sufficient computational power to run ROS, support AI model inference (e.g., for enhancing camera image quality and waste classification), and process sensor data in real time. We evaluated two popular options: the **Raspberry Pi 4 (8GB RAM)** and the **Raspberry Pi 5 (8GB RAM)**, both capable of meeting *Boat Cleaning's* demands in marine environments. The table below compares their key features to determine the best fit.

Feature	Pi 4 (8GB RAM)	Pi 5 (8GB RAM)
CPU	Quad-core Cortex-A72 @ 1.8GHz	Quad-core Cortex A76 @ 2.4GHz
RAM	8GB LPDDR4-3200	LPDDR4X-4267
Ubuntu 20.04 Support	Yes, official support and easy setup	No official support, requires custom setup

ROS Noetic Support	Yes, fully compatible	Yes, but may have compatibility issues

The **Raspberry Pi 4 (8GB)** is the better choice for running **Ubuntu 20.04** and **ROS Noetic** due to its official support and straightforward installation. The **Raspberry Pi 5 (8GB)**, while offering superior performance, lacks official Ubuntu 20.04 support, potentially complicating ROS Noetic setup. Additionally, there are other micro-computers like the **NVIDIA Jetson Nano**, but we can't choose them due to their higher cost (approximately $99) and potential setup challenges.

2.2.2 Microcontroller Selection

The secondary microcontroller is tasked solely with reading GPS data and controlling motors, operating as a slave to the Raspberry Pi 4. This division of responsibilities allows Raspberry Pi 4 to manage complex computations while the secondary microcontroller handles these specific real-time tasks. By offloading GPS data processing and motor control, the system achieves efficient performance.

The Arduino Uno has been selected for this role due to its simplicity and suitability.

Feature	**Arduino Uno Characteristics**
CPU	ATmega328P, 16 MHz

Memory	32 KB Flash, 2 KB SRAM, 1 KB EEPROM
I/O Pins	14 digital (6 PWM), 6 analog inputs
Communication	UART, SPI, I2C
GPS Shield Compatibility	Compatible with dedicated shields like the Adafruit Ultimate GPS Shield for seamless GPS integration

The Arduino Uno efficiently handles Boatcleaninge's GPS data reading (via UART with a Ublox NEO-6M) and motor control (using PWM outputs), acting as a reliable slave to the Raspberry Pi 4. The Uno's simplicity and affordability make it ideal for real-time tasks in marine environments.

2.3. Sensors

Sensors are the perceptive tools that allow *Boat Cleaning* to understand its environment and maintain situational awareness. They collect critical data for navigation, obstacle avoidance, and waste detection in challenging aquatic settings.

2.3.1 Lidar Selection

To ensure *Boat Cleaning* can effectively navigate and detect obstacles in marine environments, we evaluated three sensor types: RPLIDAR (a LiDAR-based sensor), ultrasonic sensors, and Time-of-Flight (ToF) sensors. The table below compares their key characteristics to determine their suitability for the boat's autonomous waste collection mission.

Feature	**TOF Sensor**	**Ultrasinc sensor**	**RPlidar 360°**
Working Principle	Emits infrared light pulses and measures return time for distance or depth mapping.	Emits high-frequency sound waves and measures echo return time for distance.	Emits laser pulses and measures time-of-flight to create a 360° point cloud for mapping.
Range	0,1m-12m	0.02 - 4 m	0.15 - 12 m
Field of view	2°	30-40°	360 °
Communication Protocol	UART/I2C	GPIO Timing	UART
Suitability for Cleaning Boat	Suitable for precise, short-range waste detection but restricted by its 2° FoV, requiring multiple units for broader coverage.	Useful for close-range obstacle detection but limited by narrow FoV and sensitivity to marine debris.	Ideal for creating detailed 2D maps and avoiding obstacles in open water due to its wide FoV.

The RPLIDAR remains the top choice for *Boat Cleaning* due to its 360° field of view and high accuracy, enabling comprehensive environmental mapping and navigation in complex marine settings.

2.3.2. Camera Selection

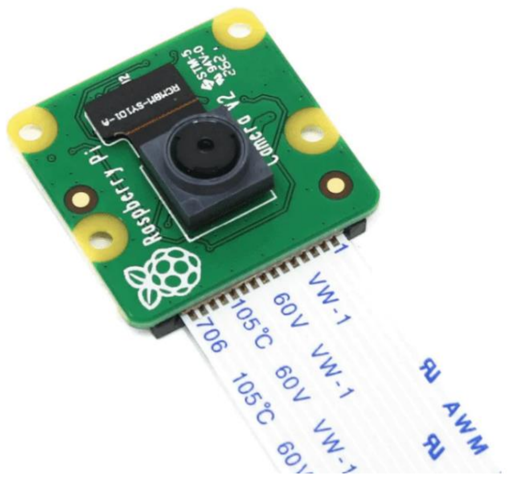
A camera serves as *Boat Cleaning '*s key sensor for visual waste detection, capturing images to identify and classify debris in marine environments. Integrated with an AI model, which requires images at a 640x640 resolution, enabling the boat to accurately target waste during its cleanup mission. I have selected a Raspberry Pi Camera, as it integrates seamlessly with the Raspberry Pi 4 , . This resolution requirement guided our research into specific Raspberry Pi Camera types suitable for the project.

The table below compares two Raspberry Pi Camera options—**Camera Module 8MP (60° FoV)**, **Camera Module 8MP (120° FoV)**.

Feature	**Camera 8MP (60° FoV)**	**Camera 8MP (120° FoV)**
Resolution	8MP (3280x2464)	8MP (3280x2464)

Field of View (FoV)	60°, focused for precise waste targeting	120°, wide for broader environmental scanning
Suitability for Boatcleaninge	Ideal for precise waste detection with AI	Better for wide-area scanning, less precise

The Raspberry Pi Camera 8MP with 60° FoV is chosen because its 8-megapixel resolution and focused 60° field of view are optimized for the AI model's 640x640 input, ensuring precise waste detection. The 120° FoV version is better suited for scanning wider areas but less effective for AI accuracy.



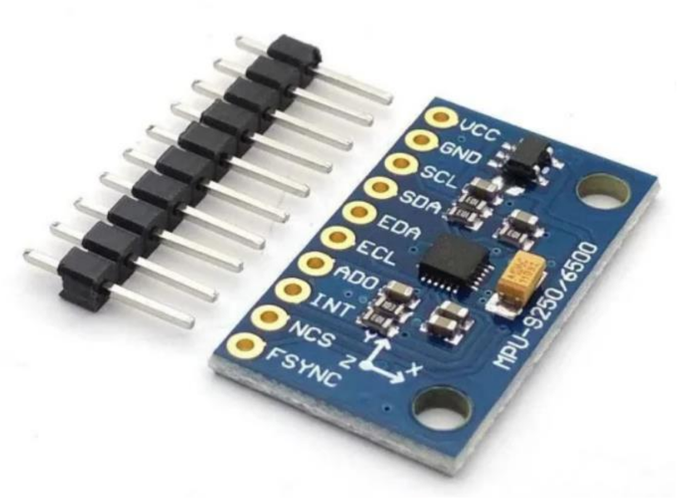
2.3.3 Gyroscope

The gyroscope is vital for autonomous navigation, measuring angular velocity to track rotational movements and ensure stability. It compensates for wave-induced motions, enabling precise heading control in challenging marine environments.

The table below compares the **6-axis IMU** and **9-axis IMU** to evaluate their suitability for *Boat Cleaning*'s orientation and navigation needs:

Feature	6-Axis IMU	9-Axis IMU
Accelerometer (3D)	Included	Included
Gyroscope (3D)	Included	Included
Magnetometer (3D)	Not included	Included
Typical Use Cases	Motion tracking, drones, basic robotics	Navigation, robotics with compass, marine applications

The 9-axis IMU was chosen due to its magnetometer, which enables absolute orientation and robust performance in any marine environment. Its protection from magnetic fields ensures reliable navigation, surpassing the limitations of a 6-axis IMU.



2.3.4 GPS and SIM Module

Why do we use GPS?

GPS is essential for the Ocean Cleaner autonomous navigation, enabling the system to follow predefined map points programmed for waste collection routes. It ensures precise self-localization, allowing robots to determine their position in marine environments accurately.

Why do we use SIM module?

The integrated SIM (GSM/GPRS) functionality enables *Boatcleaninge* to transmit real-time status updates, such as GPS coordinates and system diagnostics, for remote monitoring.

Feature	**GPS NEO-6M Micro USB**	**SIM808 GSM/GPS/GPRS Module**
GPS Chipset	u-blox NEO-6M	MT3336 (SIM808 integrated GPS)
Communication Capabilities	None (GPS only)	GSM/GPRS (quad-band 850/900/1800/1900 MHz)
Data Transmission	None	GPRS: max 85.6 kbps downlink/uplink
GPS Sensitivity	Tracking: -161 dBm, Cold start: -147 dBm	Tracking: -165 dBm, Cold start: -148 dBm

Tracking sensitivity applies when the GPS module is already locked onto satellite signals and maintaining position data. The SIM808’s -165 dBm is more sensitive than the NEO-6M’s -161 dBm, meaning it can maintain a lock on weaker signals. Cold start sensitivity applies when the GPS module starts without prior satellite data (e.g., after being powered off for a while). The SIM808’s -148 dBm is slightly better than the NEO-6M’s -147 dBm, allowing it to acquire satellites faster in poor conditions. Data Transmission via GPRS on the SIM808 (85.6 kbps) allows robots to send real-time GPS coordinates and diagnostics, a feature absent in the NEO-

6M. The SIM808 is better than the NEO-6M for the Ocean Cleaner due to its superior GPS sensitivity and added GPRS communication for remote monitoring.

2.4. Actuators

Actuators are the components that enable *Ocean Cleaner* to move and execute its waste collection mission in marine environments. They translate control signals from the processing unit into physical actions, ensuring precise navigation and operational efficiency.

To ensure optimal performance of the Ocean Cleaner, the type of motor selected should possess specific characteristics. We recommend using two underwater DC motors that can be seamlessly integrated into the dual-hull design without risking water ingress. These motors should support differential steering, enabling precise navigation and obstacle avoidance in marine environments. Choosing such motors ensures reliable and controlled propulsion, which is essential for the autonomous waste collection mission.

The table below compares the **APISQUEEN U2 MINI 1.3Kg 16V 130W** and **APISQUEEN U01 12V-16V 2Kg 390W** thrusters, evaluating their suitability for *Ocean Cleaner*'s propulsion needs:

Feature	APISQUEEN U2 MINI	APISQUEEN U01
Thrust	1.3 kg	2 kg
Voltage	12–16 V (3–4S LiPo)	12–16 V (2–4S LiPo)
Max Power	130 W	390 W
Max Current	8 A	17 A
Weight	210 g	178 g
Arduino Uno Compatibility	Yes, via PWM through motor driver	Yes, via PWM through motor driver

The **APISQUEEN U2 MINI 1.3Kg 16V 130W** thrusters were selected for *Ocean Cleaner* because their lower power consumption (130 W) compared to the U01's 390 W significantly reduces battery demands, addressing critical power supply constraints for the system.

2.5. Power System

The power system is a cornerstone of the *Ocean Cleaner* project, as it governs the hours of navigation and directly influences mission duration and efficiency in marine environments. Initially, I decided using a single battery to power all hardware components, including the motors, Raspberry Pi, Arduino, and SIM808 module. This seemed like a straightforward solution to streamline the design. However, the motors' substantial power demands—each requiring 130 watts and drawing up to 8A of current—revealed a flaw in this approach. A single battery risked overheating under such a heavy load, which could compromise the performance and reliability of the other equipment.

To overcome this challenge, I shifted to a distributed power system. I decided to use separate LiPo batteries for each motor, paired with a power bank to supply the Raspberry Pi, Arduino, and SIM808 module. This solution spreads the power load across multiple sources, reducing the risk of overheating and ensuring that all components operate smoothly and efficiently throughout the mission. By addressing the motors' high current draw independently, this design enhances the system's overall stability and supports the *Ocean Cleaner*'s goals in marine cleanup efforts.

2.5.1. LiPo Battery Selection

For the *Ocean Cleaner* project's propulsion system, we chose the **Zeee 4S 14.8V 5200mAh 100C LiPo Battery with EC5 Connector**. This battery was selected to meet the high-performance demands of the underwater thrusters while ensuring reliability and efficiency in a marine environment.

- **Voltage (14.8V)**: The 4S configuration delivers 14.8V, which is ideal for powering the motors efficiently, providing the necessary thrust for navigation.
- **Capacity (5200mAh)**: With a 5200mAh capacity, this battery strikes a balance between weight and runtime, allowing *Ocean Cleaner* to operate for extended periods without adding excessive bulk.
- **Discharge Rate (100C)**: The 100C rating enables the battery to supply up to 520A of current (5200mAh × 100C / 1000), far exceeding the 16A needed for two thrusters (8A each). This ensures consistent performance during high-demand situations like wave navigation or rapid maneuvers.

The Zeee 4S LiPo battery's robust design and high discharge capability make it an excellent match for Ocean Cleaner's propulsion needs.

5.2. Power Bank Selection

For the control electronics of Ocean Cleaner, we selected the TECTIN 20000mAh 66W Power Bank with the following specifications: wired connectivity, 66W power output, 20000mAh battery capacity, USB Type-C input, 2 x USB outputs and fast charge capability. This power bank was chosen to provide a stable and versatile power source for the Raspberry Pi and SIM808 module.

- **Capacity (20000mAh)**: The 20000mAh capacity ensures long-lasting power for the Raspberry Pi, Arduino, and SIM808 module, supporting extended missions without frequent recharging.
- **Power Output (66W)**: With a 66W output, it easily handles the combined power needs of the Raspberry Pi (15-20W), Arduino (1-2W), and SIM808 module (2-10W), with ample reserve capacity.
- **Two Ports**: The two USB outputs allow simultaneous powering of the Raspberry Pi and SIM808 module, streamlining the power setup and reducing complexity.
- **Fast Charge**: The fast charge feature reduces downtime by quickly replenishing the power bank between missions.


100%
66w
- FAST CHARGING -

References:

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