OCEAN VOYAGER FOR EARLY DETECTION OF PRE-MICROPLASTIC MARINE DEBRIS

Advaith Rajagopalan

BASIS Independent Silicon Valley, San Jose, CA, USA
rajagopalan.advaith@gmail.com

Abstract

Plastic pollution in marine environments has escalated into a global ecological crisis, primarily due to the formation of microplastics that persist indefinitely and infiltrate marine food chains. Microplastics originate from the degradation of larger plastic debris through ultraviolet radiation, wave-induced mechanical stress, and prolonged exposure to ocean currents. Once fragmented, these particles are extremely difficult to remove using existing cleanup technologies. Current mitigation strategies, such as river-mouth interception systems and large-scale cleanup vessels, address only part of the problem and fail to prevent widespread microplastic formation.

This research presents the design and development of an autonomous surface vehicle (ASV) intended to detect and localize floating debris at an early stage, before fragmentation occurs. The system integrates thermal imaging, vision-based sensing, onboard computation, and autonomous navigation to identify debris clusters in real time. Unlike satellite-based approaches, which lack sufficient spatial resolution to detect small or dispersed debris, the proposed ASV operates at close range and dynamically adapts to environmental conditions. The project demonstrates a scalable and cost-effective approach that complements existing marine debris mitigation efforts by focusing on prevention rather than post-fragmentation cleanup.

Keywords

Index Terms— Autonomous surface vehicle (ASV); Marine debris detection; Microplastic prevention; Thermal imaging; Multi-camera vision validation; Hierarchical sensing; Autonomous navigation; Differential thrust control; Grid-based exploration; Real-time classification; Onboard computation; Power distribution (LiPo/UBEC)

1. Introduction

Marine plastic pollution has emerged as one of the most persistent environmental challenges of the 21st century. Each year, millions of tons of plastic waste enter the world's oceans through rivers, coastal runoff, industrial discharge, and improper waste management. Over time, ocean currents transport this debris into large-scale circulation systems known as gyres. There are currently five major ocean gyres worldwide, each acting as a convergence zone where floating debris accumulates [6], [7].

The most well-known of these is the Great Pacific Garbage Patch, which is estimated to contain approximately 1.8 trillion pieces of plastic debris and covers an area roughly twice the size of Texas. Contrary to common perception, these regions are not composed primarily of large visible objects, but rather of vast quantities of microplastics suspended near the ocean surface. Microplastics form when larger plastic objects degrade due to prolonged ultraviolet exposure, wave action, and repeated mechanical abrasion [8], [9].

Once plastic debris reaches the microplastic scale, removal becomes exceptionally difficult. Current technologies are not capable of efficiently collecting microplastics across large oceanic regions, making direct cleanup impractical. As a result, prevention has become a critical focus of marine pollution research. By removing plastic debris before it fragments, the total quantity of microplastics entering the marine ecosystem can be reduced [4], [9].

Several approaches have been proposed to address this issue. River-mouth interception systems capture debris before it enters the ocean, targeting one of the largest sources of plastic pollution. Satellite-based monitoring enables large-scale observation of debris accumulation zones, while ship-based cleanup systems focus on collecting debris in high-density areas. However, these solutions suffer from significant limitations. River blockers do not capture all debris, satellites lack sufficient resolution to detect small or sparsely distributed objects, and manned vessels are costly and limited in operational duration [4], [5].

These limitations highlight the need for an intermediate-scale solution capable of detecting debris clusters early and autonomously. This research proposes an autonomous surface vehicle that bridges the gap between large-scale monitoring and localized cleanup. By operating directly on the ocean surface and integrating multi-sensor perception with autonomous navigation, the system aims to detect debris before it degrades into microplastics.

2. Methods

2.1. Hardware and Structural Design

The autonomous surface vehicle (ASV) was designed with an emphasis on mechanical stability, waterproofing, and precise maneuverability. A catamaran hull configuration was selected due to its wide base, low center of gravity, and inherent resistance to roll and sway. Compared to monohull designs, the dual-pontoon structure provides improved lateral stability, which is essential for maintaining consistent sensor orientation and minimizing motion-induced noise in visual and thermal data acquisition.

Each pontoon supports one propulsion unit, enabling symmetric thrust distribution. Two Blue Robotics T200 thrusters are mounted beneath the pontoons approximately 7–10 cm forward of the stern. This placement aligns the thrust vectors near the vehicle's center of mass, reducing yaw instability and enabling predictable differential thrust control. Each thruster is secured using a four-point mounting pattern that matches the factory-defined screw layout of the T200 thrusters. Mounting holes were drilled directly into the hull, and thrusters were mechanically fastened using corrosion-resistant screws.

To prevent water ingress at the thruster–hull interface, a layered sealing strategy was implemented. Epoxy resin was applied around all mounting holes to create a rigid, waterproof bond, followed by silicone sealant to provide flexible sealing and accommodate minor structural deformation. This redundancy ensures long-term waterproofing under vibration and prolonged exposure to water.

The electronics compartment is located at the center of the hull and accessed through a removable lid. All seams, joints, and lid interfaces are sealed using silicone sealant. Cable glands are used at all wire entry points to maintain watertight integrity while allowing necessary electrical connections between internal electronics and external components such as thrusters and sensors.

Vibration damping pads were installed beneath the Raspberry Pi, battery tray, and auxiliary circuit boards. These pads reduce mechanical vibration transmitted from the thrusters and water motion, protecting sensitive electronics and improving sensor accuracy. Reducing vibration is particularly important for vision-based sensing, as even small oscillations can degrade image quality and classification performance.

Figure 1 illustrates the overall structural layout of the ASV, including hull geometry, thruster placement, electronics compartment location, and sensor mounting positions.

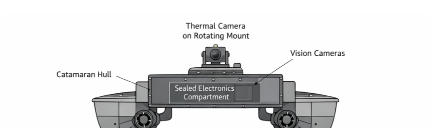


Figure 1. *Structural layout of the autonomous surface vehicle, showing the catamaran hull, thruster placement beneath each pontoon, sealed electronics compartment, and sensor mounting locations.*

2.2. Electrical System Design

The electrical architecture of the ASV was designed to clearly separate propulsion power, regulated logic power, and control signals to ensure safe and reliable operation. A multi-cell lithium-polymer (LiPo) battery serves as the primary power source. Power distribution begins at a male XT60 battery connector, which interfaces with a female XT60 three-way splitter.

Two branches of the splitter supply unregulated battery power directly to the electronic speed controllers (ESCs) for the left and right thrusters. ESCs are required because the Raspberry Pi cannot drive high-current motors directly. Each ESC converts low-power control signals into the high-current motor drive required by the thrusters, enabling precise modulation of thrust.

The third branch of the XT60 splitter supplies power to a UBEC (Universal Battery Elimination Circuit). The UBEC regulates the battery voltage down to a stable low-voltage output suitable for onboard electronics. Voltage regulation is critical, as fluctuations or overvoltage could permanently damage the Raspberry Pi, sensor boards, or driver modules.

From the UBEC, power is routed through jumper wires to a two-way power splitter. One output supplies power to the Raspberry Pi via a USB-C connection, while the second output powers a peripheral driver board through a screw terminal interface. Ring terminals and screw terminals are used throughout the system to ensure secure mechanical connections, especially where wire gauge differences prevent direct connector compatibility.

All electrical connections are insulated and strain-relieved to reduce the risk of short circuits or wire fatigue. This structured power flow ensures that propulsion loads do not interfere with computation or sensor performance.

Figure 2 presents a schematic representation of the ASV power distribution system.

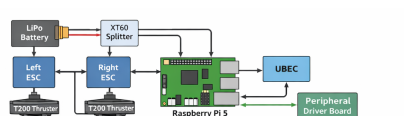


Figure 2. *Electrical power distribution schematic showing LiPo battery, XT60 splitter, ESCs for thrusters, UBEC*

voltage regulation, Raspberry Pi power input, and peripheral driver board.

2.3. Control and Signal Architecture

The Raspberry Pi serves as the central control unit, managing sensor input, navigation logic, and actuator control. Communication between the Raspberry Pi and peripheral devices is handled through a combination of GPIO pins, ribbon cables, and serial communication protocols.

Three vision cameras and one thermal camera are integrated into the system. Vision cameras transmit image data through ribbon cables, which provide high-bandwidth video transfer directly to the processing unit. However, because the Raspberry Pi supports a limited number of native camera interfaces, a multi-camera adapter board is used. This adapter expands the number of available camera inputs and communicates with the Raspberry Pi via GPIO connections.

GPIO pins are also used for control signals to the peripheral driver board. The driver board acts as an intermediary between the Raspberry Pi and devices that cannot interface directly with GPIO, such as ESCs and servo motors. Specifically, the driver board controls:

1. Signal communication with both ESCs for thruster control

2. A servo motor that rotates the thermal camera mount through a full 360-degree range

The servo-driven thermal camera mount allows panoramic scanning of the surrounding environment. After completing a full rotation, the mount reverses direction to prevent excessive wire twisting, ensuring mechanical longevity.

This layered signal architecture separates high-bandwidth data transmission, low-power control signaling, and high-current power delivery, improving system reliability and simplifying debugging.

Figure 3 illustrates the control and data flow architecture of the ASV.

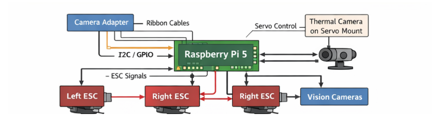


Figure 3. *Control and signal flow diagram showing Raspberry Pi communication with camera adapter, driver board, ESCs, servo motor, and sensors.*

2.4. Software Design

Autonomous operation is governed by a sensor-driven feedback loop implemented on the onboard computer. The system follows a staged detection strategy designed to balance computational efficiency with detection accuracy.

The detection process begins with the thermal camera performing a 360-degree scan of the surrounding environment. The scan is conducted in angular increments, during which the system analyzes temperature variations on the water surface. Floating debris often exhibits thermal properties distinct from the surrounding seawater, producing detectable temperature anomalies.

Upon completing a full scan, the rotating mount reverses direction to return the thermal camera to its forward-facing orientation, preventing excessive cable twisting. Detected anomaly coordinates are stored and prioritized based on intensity and spatial consistency.

The ASV then navigates toward selected target regions using differential thrust control. As the vehicle approaches a target, vision cameras are activated to capture high-resolution imagery. These images are processed to confirm the presence of debris and filter out false positives such as wave reflections or biological material.

Navigation and sensing occur continuously, with the system adjusting its trajectory in response to sensor feedback. Once deployed, the ASV operates autonomously without human intervention, making it suitable for long-duration monitoring tasks.

2.5. Exploration Strategy

The autonomous surface vehicle employs a structured exploration strategy designed to systematically scan a defined area for potential marine debris. As shown in **Figure 4**, the robot begins at a designated center point and rotates incrementally, sampling thermal data at each angular position. This approach enables panoramic thermal coverage without requiring linear movement during initial scanning.

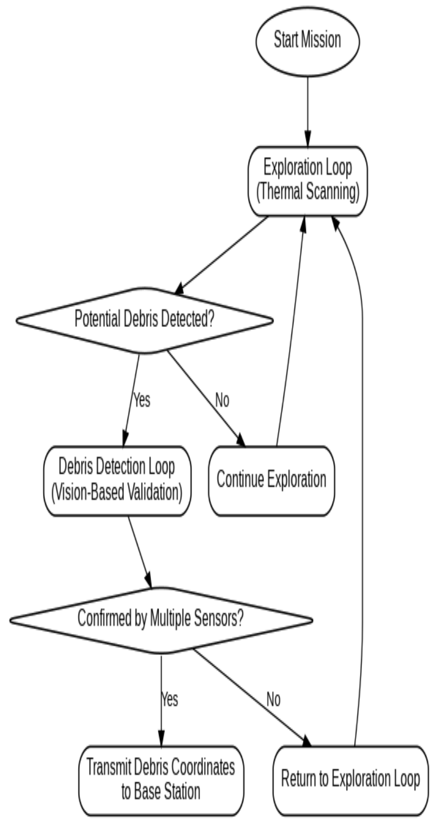
If the thermal sensor detects a temperature signature consistent with floating debris, the corresponding coordinates are recorded and passed to the debris detection loop. In the absence of detection, the robot completes a full rotation before relocating to the next center point based on its current position and directional orientation. This grid-based exploration method ensures complete area coverage while maintaining low computational and energy overhead.

2.6. Debris Detection and Validation

Once a candidate debris location is identified, the system transitions to the debris detection loop illustrated in **Figure 5**. In this phase, the robot advances linearly while capturing images using multiple vision sensors. Captured images are classified in real time to determine the presence of debris.

If debris is detected by multiple vision sensors, the system confirms the detection and transmits the debris coordinates to a base station for further action. In cases where debris is not confirmed, the robot performs incremental rotational adjustments to refine its viewpoint. If confirmation remains unsuccessful, the robot returns to the exploration loop, ensuring that false positives do not interrupt the overall mission.

High-Level System Flow



2.7. Novelty and Impact

The novelty of this work lies in its prevention-focused approach to marine plastic pollution through early-stage debris detection rather than post-fragmentation cleanup. Unlike existing strategies that rely on large-scale satellite imagery or fixed river interception systems, the proposed autonomous surface vehicle operates at an intermediate spatial scale and integrates thermal sensing with multi-camera vision validation to detect debris before it degrades into microplastics. The hierarchical sensing architecture reduces computational overhead while improving detection reliability, and the fully autonomous exploration and validation loops enable systematic area coverage without human intervention. The impact of this system is its potential to complement current cleanup efforts by providing precise, real-time debris location data, allowing targeted and resource-efficient mitigation strategies that can significantly reduce the long-term accumulation of microplastics in marine environments.

3. Results and Discussion

Integrating the detailed mechanical, electrical, and control architecture significantly improves the robustness and reproducibility of the ASV design. The catamaran hull and symmetric thruster placement enable predictable motion control, while vibration damping and waterproofing measures ensure reliable long-term operation. The structured power distribution system prevents electrical interference between propulsion and logic components, a common failure point in small-scale marine robots.

The staged sensing approach—thermal scanning followed by vision-based confirmation—reduces unnecessary computation and enables efficient detection of debris clusters that would be missed by satellite imagery. While testing has been limited to controlled environments, the design choices documented here provide a strong foundation for future open-water deployment.

4. References

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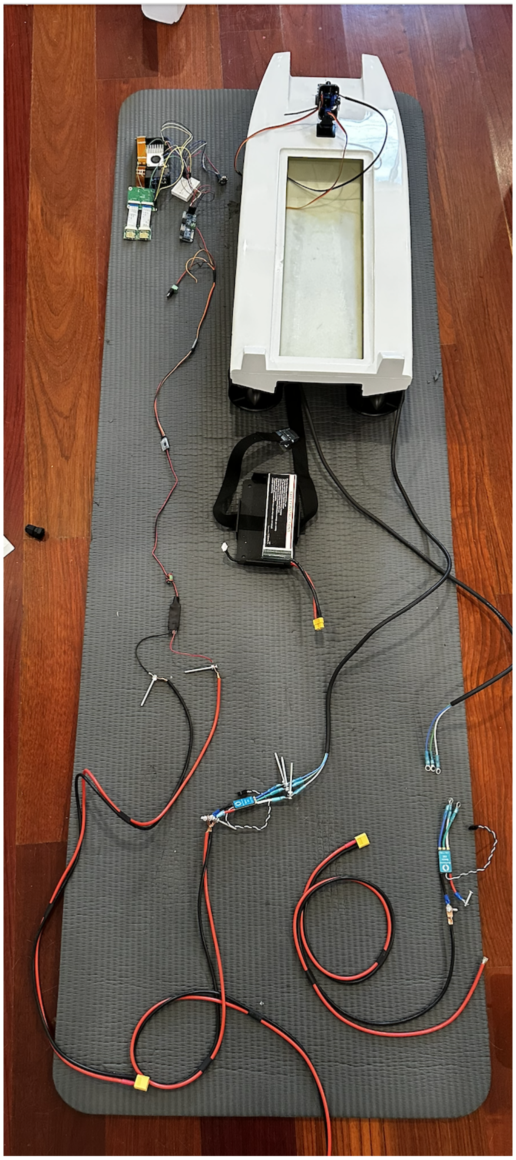
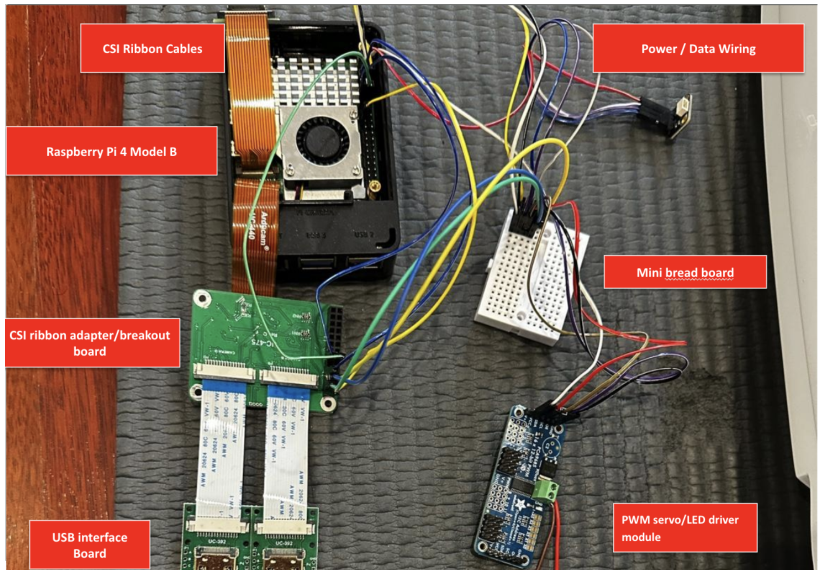
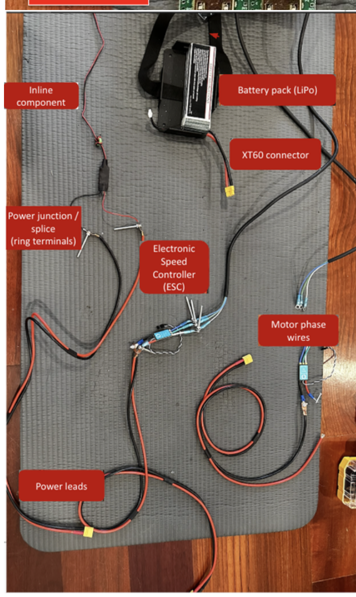
Appendix

Appendix A: Hardware Integration and Wiring Photographs
Appendix B: Overall System Connection Diagram
Appendix C: Electrical Power Distribution Diagram
Appendix D: Detailed Communication and Control Flow Diagram
Appendix E: Exploration Loop for Autonomous Surface Vehicle
Appendix F: Debris Detection Loop Using Multi-Sensor Vision Confirmation

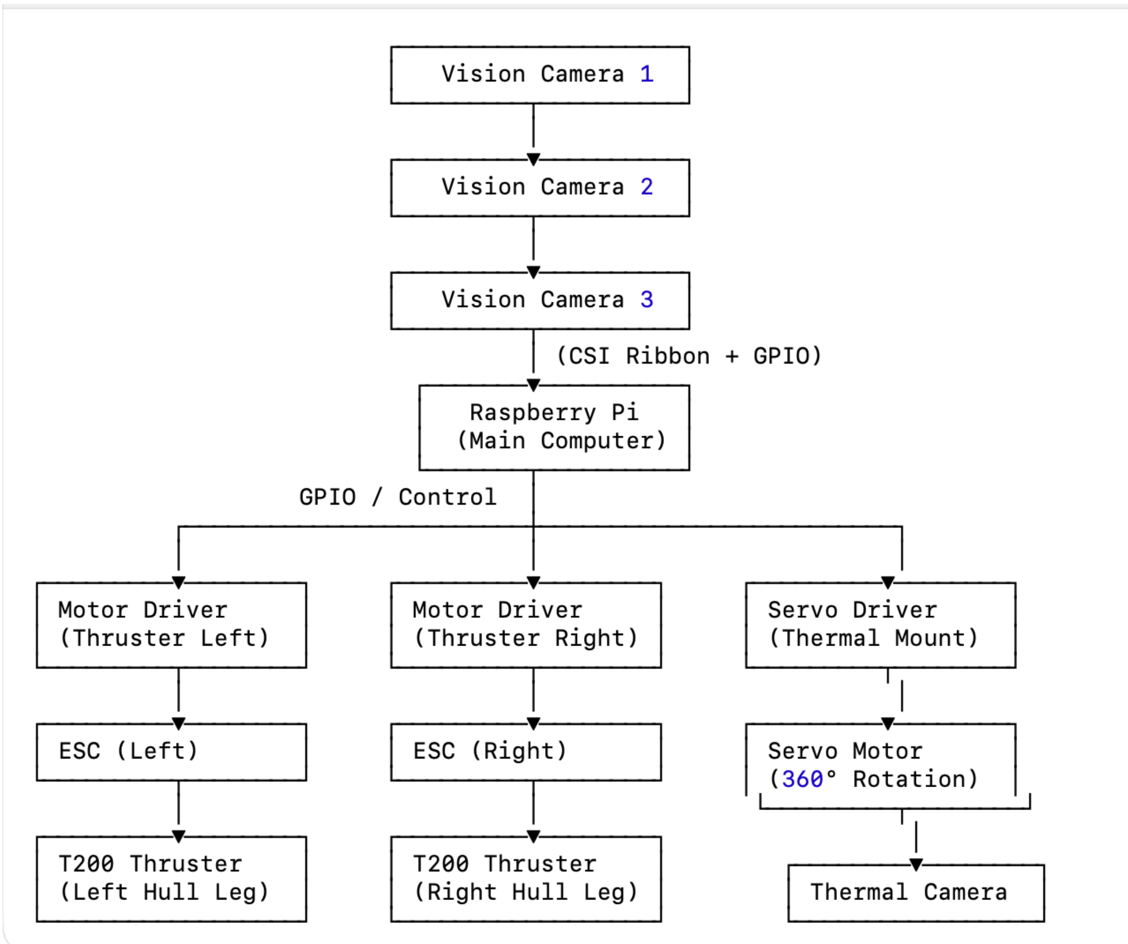
Appendix A: Hardware Integration and Wiring Photographs



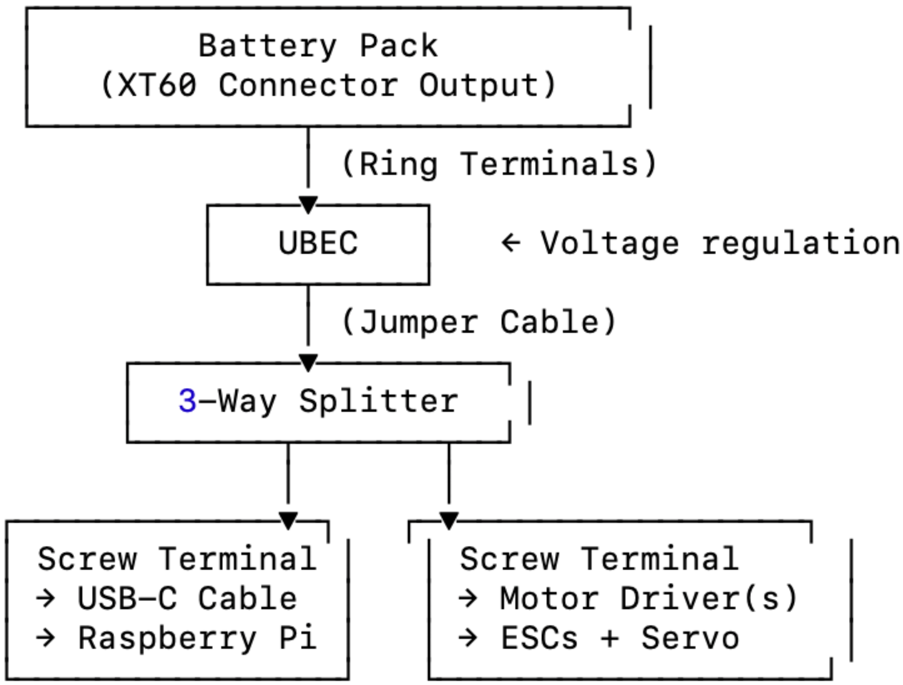




Appendix B: Overall System Connection Diagram



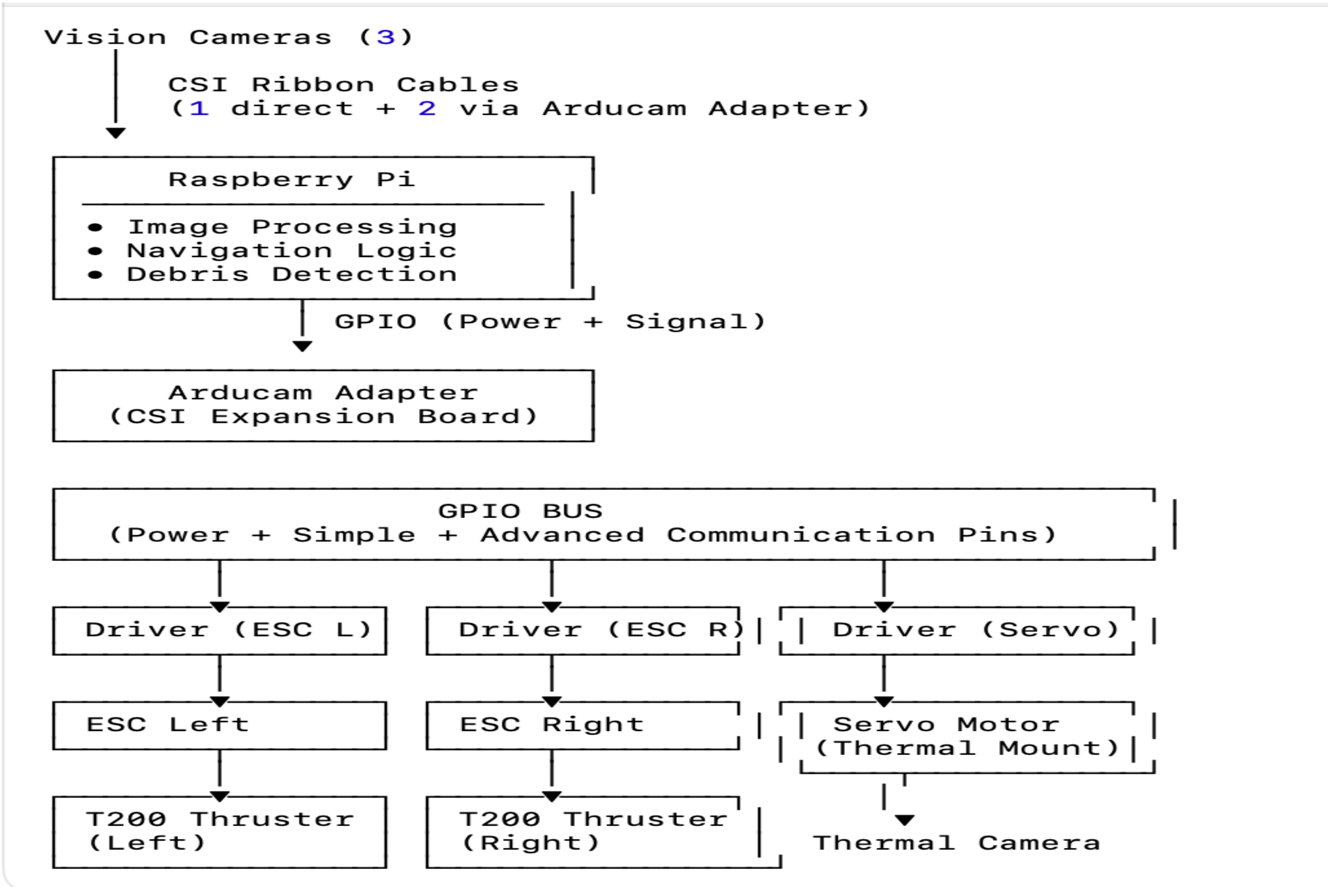
Appendix C: Electrical Power Distribution Diagram (Battery -> UBEC -> Loads)



Key Notes:

- UBEC converts battery output to safe voltage for the Raspberry Pi.
- Driver receives dual power: directly from battery and GPIO.
- Thermal sleeves + foam pads protect wiring and components.

Appendix D: Detailed Communication & Control Flow Diagram

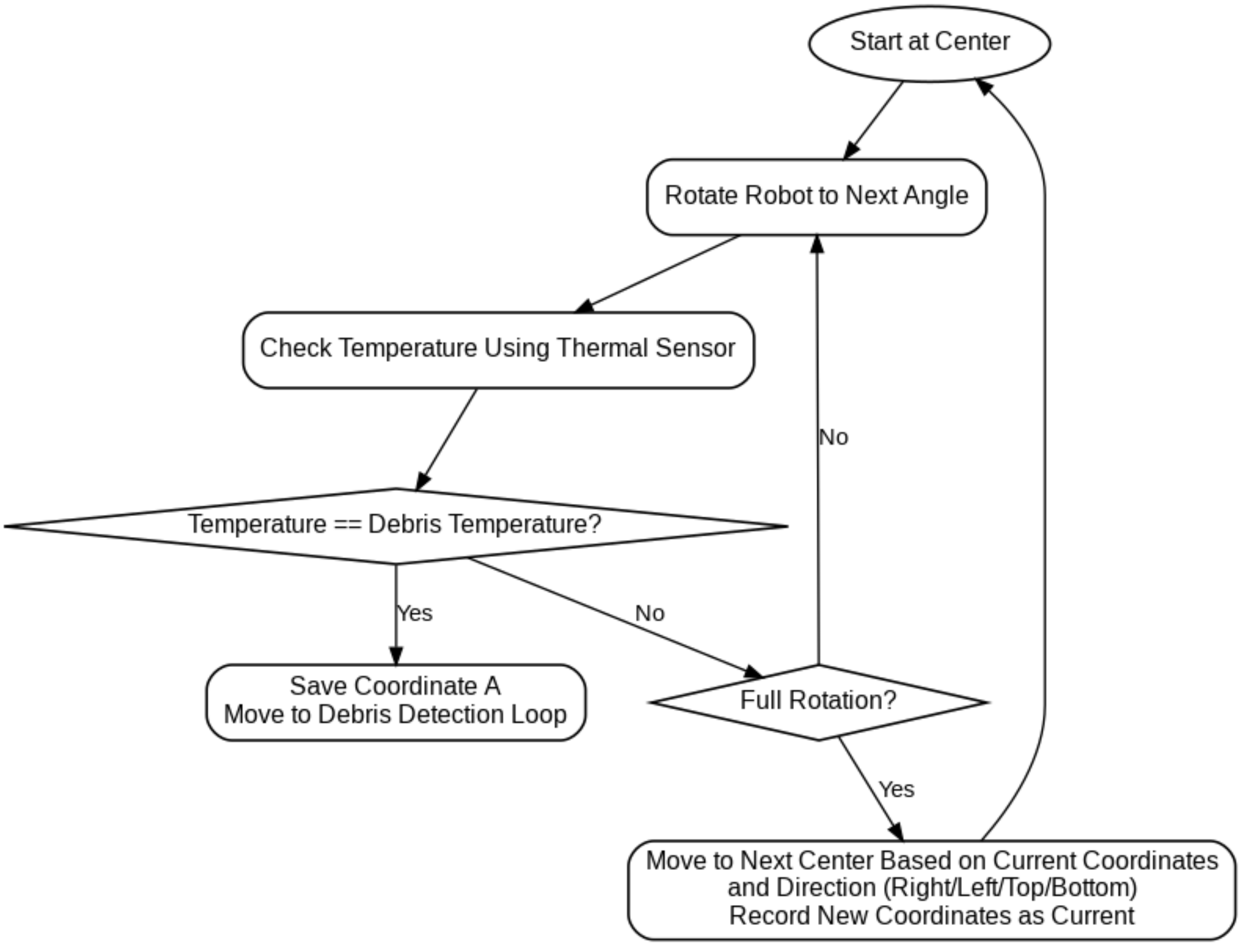


Communication Characteristics

- Thruster control: Computer -> Driver -> ESC -> Thruster (command-driven)
- Servo control: Computer -> Driver -> Servo (bidirectional feedback possible)
- **Sensors**: Powered via GPIO, data flows to Raspberry Pi

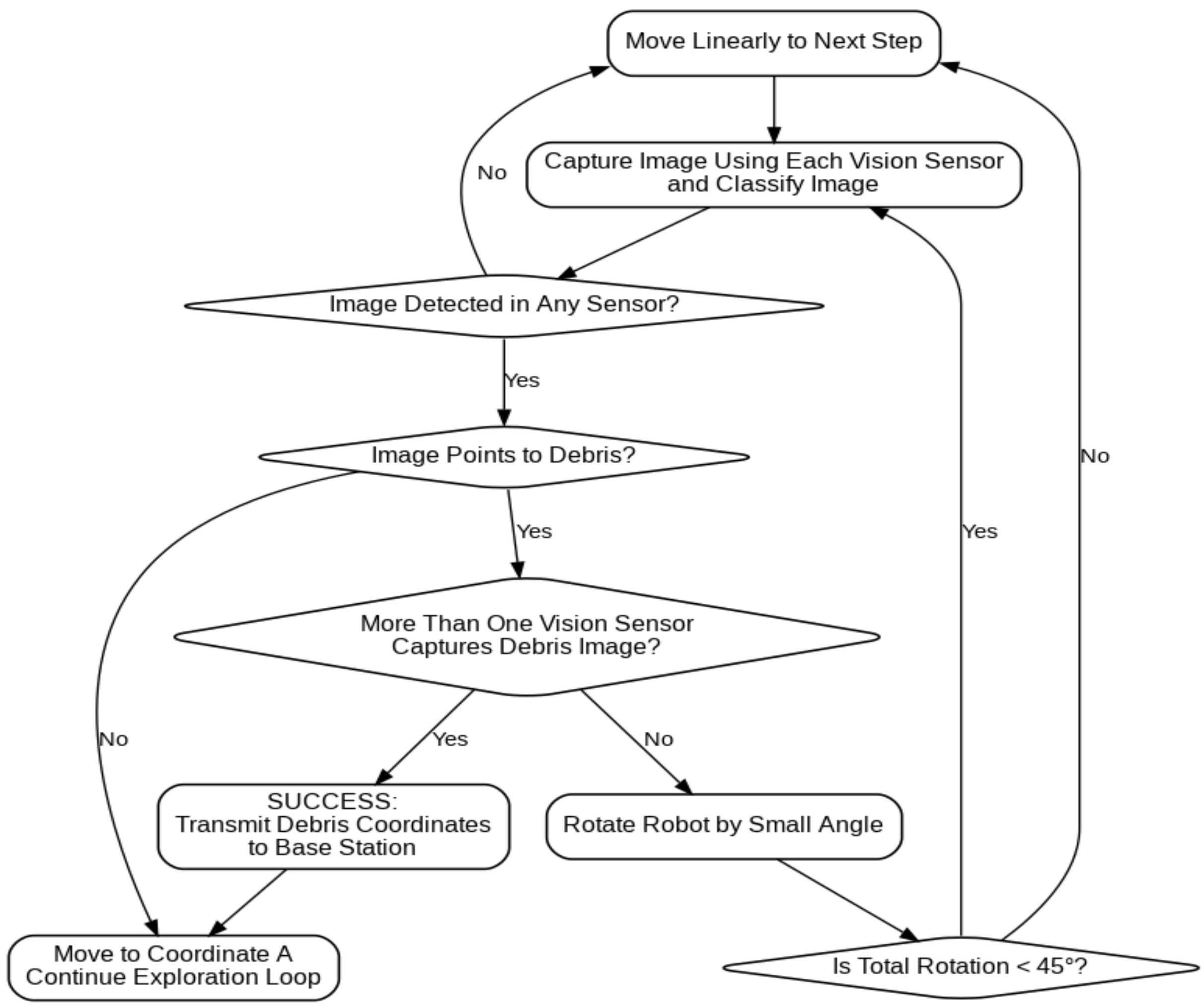
Appendix E. Exploration Loop for Autonomous Surface Vehicle

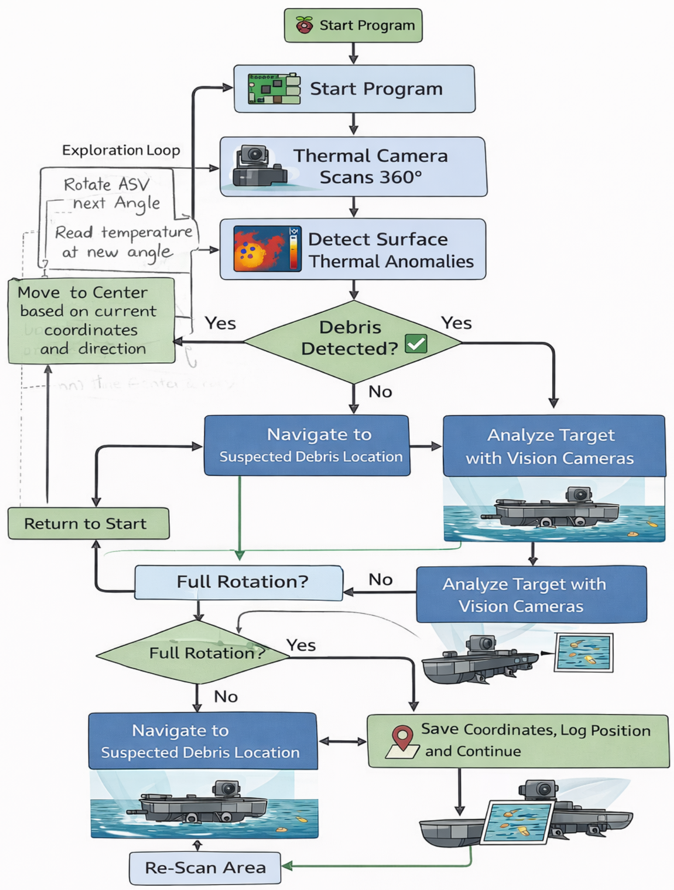
This figure illustrates the exploration loop executed by the autonomous surface vehicle during area scanning. Starting from a defined center point, the robot incrementally rotates and samples thermal data using an onboard thermal sensor. If a temperature signature corresponding to debris is detected, the robot records the location and transitions to the debris detection loop. If no debris is detected after a full rotation, the robot moves to the next center based on its current coordinates and directional orientation, enabling systematic coverage of the search area.



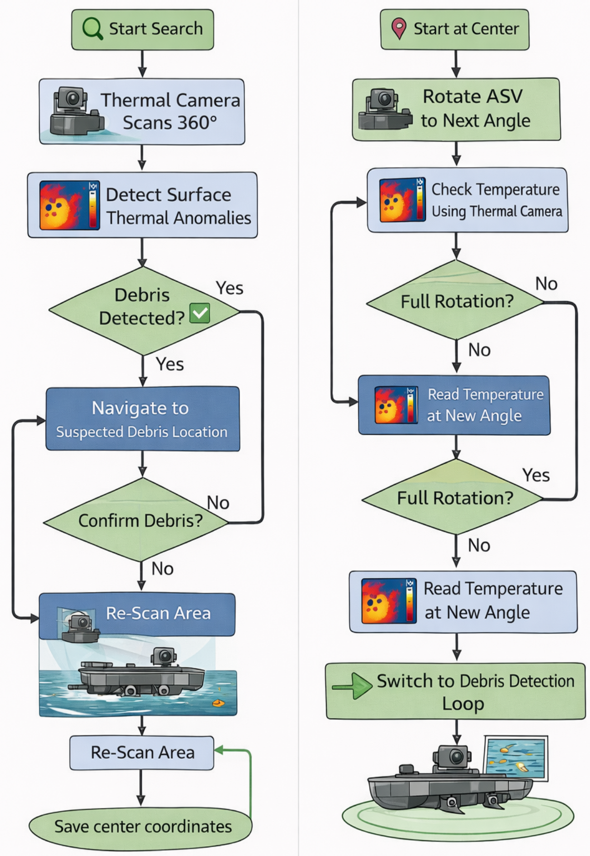
Appendix F: Debris Detection Loop Using Multi-Sensor Vision Confirmation

This figure shows the debris detection loop initiated after a potential debris location is identified by the exploration loop. The robot moves linearly while capturing images from multiple vision sensors and classifying them in real time. If debris is confirmed by more than one vision sensor, the robot transmits the debris coordinates to a base station. If confirmation fails, the robot performs controlled rotational adjustments or returns to the exploration loop, ensuring robust validation and minimizing false positives.





Autonomous Surface Vehicle Sensor Workflow



Debris Detection Loop

Exploration Loop