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Design and development of BLUECARV: A remotely operated underwater vehicle for blue carbon monitoring and marine ecosystem conservation

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Abstract: Blue carbon ecosystems such as mangroves, seagrasses, and coral reefs require frequent and accurate monitoring, yet traditional diver-based surveys are limited by depth, cost, and operational risks. This study aims to develop BLUECARV, a low-cost and modular Remotely Operated Vehicle (ROV) designed to enhance ecological observation and environmental data acquisition in coastal habitats up to 100 meters depth. The system integrates a 3-axis manipulator arm, multi-parameter environmental sensors (temperature, salinity, pH, and pressure), and an Ultra HD underwater camera within a hybrid modular architecture that supports flexible payload configurations. BLUECARV was fabricated using corrosion-resistant materials and evaluated through laboratory and field tests, with performance metrics including maneuverability, sensor accuracy, latency, and depth-holding capability. The results show stable six-degree-of-freedom maneuvering, ±0.1 m depth stability, sensor deviations below ±1%, and video latency under 150 ms, while the manipulator achieved a 95% object-handling success rate. These findings demonstrate that BLUECARV provides reliable visual and environmental data for blue carbon ecosystem monitoring. Its affordability, modularity, and operational stability offer practical benefits for long-term coastal habitat assessment, biodiversity surveys, and community-level conservation, while enabling future upgrades such as AI-based navigation and advanced monitoring sensors.

Keywords: *Blue carbon monitoring, IoT for ocean monitoring, Manipulator 3-axis, Marine conservation, ROV BLUECARV, Underwater robotics.*

1. Introduction

Blue carbon ecosystems, including mangroves, seagrasses, and coral reefs, play a vital role in absorbing atmospheric CO_2 and sustaining marine biodiversity [1]. However, manual monitoring using divers remains costly, risky, and limited by depth and duration [2, 3]. Most commercial remotely operated vehicles (ROVs) are designed for industrial purposes and are prohibitively expensive, making them unsuitable for ecological research [4]. To overcome these challenges, the BLUECARV system has been developed as a cost-effective, modular, and eco-friendly ROV platform to support blue carbon research and marine habitat conservation.

ROVs have revolutionized underwater monitoring due to their ability to operate safely in hazardous environments while providing live video and sensor feedback [5, 6]. However, existing commercial models prioritize industrial payloads and deep-sea operations, often exceeding USD 50,000 per unit [7]. Although open-source platforms such as BlueROV2 and OpenROV have improved accessibility, challenges remain in sensor integration, maneuverability in shallow coastal zones, and task-oriented capabilities essential for blue carbon research.

Previous research has demonstrated the effectiveness of time-reversal and spatial diversity techniques in enhancing underwater acoustic communication reliability within shallow-water

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environments [8, 9]. Building upon these advancements in communication robustness, the BLUECARV platform extends this approach toward real-time data transmission and environmental sensing, thereby enabling integrated monitoring and analysis of blue carbon ecosystems.

To address these limitations, this study introduces the BLUECARV (Blue Carbon ROV), a modular and sustainable underwater vehicle tailored for shallow to mid-depth ecological observation. The system integrates six vector thrusters, providing six degrees of freedom, a three-axis manipulator arm for physical interaction, and a suite of environmental sensors that measure temperature, salinity, dissolved oxygen, and pH. An Ultra HD camera enables high-resolution visual mapping for habitat and biomass analysis.

Structurally, BLUECARV emphasizes hydrodynamic stability, corrosion resistance, and energy efficiency. Its aluminum-polycarbonate frame, optimized via Computational Fluid Dynamics (CFD), ensures operational stability. At the same time, a hybrid power system combining lithium-ion batteries and tethered communication enables up to four hours of continuous use. Moreover, the design minimizes sediment disturbance and underwater noise to reduce ecological impact [10].

Aligned with the United Nations Sustainable Development Goals (SDG 13 and SDG 14), BLUECARV strengthens local capacity in sustainable ocean technology and contributes to evidence-based conservation. This paper presents the system's design, fabrication, and validation, including architecture details, sensor integration, and performance evaluation from laboratory and field tests. The BLUECARV prototype demonstrates Indonesia's capability to develop indigenous marine robotic systems that advance blue carbon monitoring and global climate resilience.

2. Related Work

Remotely Operated Vehicles (ROVs) have become indispensable tools in underwater inspection, industrial maintenance, and scientific research. In industrial domains, high-end ROVs provide robust payload capacity, long tethered operation, and advanced sensor suites, enabling deep-water and heavy-duty tasks such as pipeline inspection and offshore intervention [11]. However, the cost and complexity of these systems restrict their adoption for routine ecological monitoring and community-scale conservation programs. Over the past five years, there has been a marked shift toward lower-cost, modular ROV platforms and research efforts that adapt these vehicles for environmental applications, aiming to strike a balance between affordability, portability, and scientific utility [12]. Recent studies also highlight the emergence of compact, AI-assisted ecological ROVs designed specifically for habitat assessment in shallow-water environments [13].

One of the most influential accessible platforms is the BlueROV2 (Blue Robotics), an open-source-inspired design that democratized small ROV construction and research [14]. BlueROV2's six-thruster configuration, extensive community documentation, and modular payload options have made it a popular baseline for academia and small-scale monitoring initiatives. Several studies have used BlueROV2 or its derivatives to explore control strategies, simulation benchmarking, and environmental survey workflows [11]. Despite these successes, the BlueROV2 and similar small commercial ROVs often require substantial integration work to host scientific sensors, manipulator arms, or photogrammetry rigs needed for blue carbon metrics. Moreover, their power budgets and tether management are frequently not optimized for intensive field campaigns in shallow, vegetated coastal zones where maneuverability and minimized seabed disturbance are critical [15]. Recent evaluations indicate that shallow-water ecological missions are increasingly requiring ROVs with improved stabilization and low-disturbance propulsion systems to minimize sediment resuspension [16].

Recent literature highlights the growing interest in applying ROVs and other unmanned platforms specifically to blue carbon monitoring and coastal habitat assessment. Remote sensing (satellite and airborne) remains indispensable for large-scale mapping, but in situ methods such as imagery, photogrammetry, and sediment sampling are necessary for ground-truthing and biomass carbon estimation [11, 14]. In this context, small ROVs equipped with high-resolution cameras and environmental probes can fill a critical niche, enabling spatially explicit, repeatable observations in mangrove roots, seagrass meadows, and shallow reef systems [17]. However, reviews of robotic efficacy in reef and seagrass monitoring indicate that most existing robotic deployments primarily focus on passive observation (video transects) rather than interactive sampling or manipulative tasks required for sediment cores or targeted specimen collection [14]. This gap limits the capability of ROVs to deliver the full suite of measurements necessary for accurate blue carbon accounting. Recent technological advancements have further emphasized the need for integrated sensor–AI pipelines in benthic habitat reconstruction and real-time ecological classification; however, many commercial ROVs lack the modularity to support such configurations [18].

Several applied projects and reports from the last few years document attempts to adapt ROV technology for ecological surveillance. For instance, regional projects have trialed observation-class ROVs for marine pest surveillance and coastal monitoring, demonstrating that modest design modifications such as enhanced lighting, mounting rigs, and simple navigational aids can significantly improve ecological data quality [19]. Similarly, hybrid approaches that pair unmanned surface vehicles (USVs) with tethered ROVs have been explored to expand range while maintaining precise underwater control for in situ sampling [20]. These initiatives collectively demonstrate feasibility yet also reinforce the need for a bespoke platform combining manipulators, tailored sensors, low cost, and shallow-water maneuverability.

Another productive line of recent work focuses on enhancing data value from small ROVs through improved sensing and analytics. The integration of photogrammetry workflows, AI-based image analysis, and GNSS-correction techniques enables quantitative mapping of benthic cover and biomass from imagery collected by remotely operated platforms [11, 15, 17]. Yet, implementing such pipelines reliably in turbid, structurally complex coastal environments places high demands on camera stabilization, lighting, and platform positioning requirements that many off-the-shelf small ROVs do not meet without significant customization [15].

3. Methodology

The development of the BLUECARV ROV followed a systematic engineering process involving design, component integration, and performance validation. The ROV frame was fabricated using corrosion-resistant aluminum alloy and polycarbonate housing to withstand hydrostatic pressure up to 10 bar. The propulsion system employs six thrusters in a vector configuration, enabling stable three-dimensional maneuverability.

The 3-axis manipulator arm is powered by waterproof servo actuators, providing precise underwater interaction without damaging fragile structures. Environmental sensors, including temperature, salinity, and pH, are interfaced via a central microcontroller for real-time acquisition. A high-definition underwater camera provides visual feedback to the surface operator, while control and data transmission are managed through a tethered Ethernet line.

The overall design methodology follows a design–build–test–iterate approach based on the classical mechatronics development cycle [21]. The main objective was to produce a cost-efficient, robust, and modular ROV platform for shallow to medium-depth operations (up to 100 m). Each subsystem: mechanical, electrical, software, and sensory, was designed for compatibility, maintainability, and scalability for future research applications.

3.1. System Design Framework

Operational requirements were defined through consultations with marine biologists, environmental engineers, and conservation teams in the Surabaya coastal region. The ROV was specified to operate at depths of up to 100 m, sustain four-hour missions, carry a 5 kg payload, and collect environmental data. CAD modeling was used to visualize frame geometry, thruster layout, and payload modules. The structural integrity was verified via finite element analysis under simulated hydrostatic pressure equivalent to 10 bar.

The final ROV structure adopts a compact rectangular layout (0.8 m × 0.6 m × 0.5 m), providing an optimal balance between hydrodynamic efficiency and component space. The frame is built from marine-grade aluminum alloy (6061-T6) due to its superior strength-to-weight ratio and corrosion resistance, supported by transparent polycarbonate enclosures. All metallic parts were anodized, and exposed connectors were sealed using silicone-based anti-corrosion coating to mitigate galvanic corrosion common in mixed-material underwater assemblies [22]. Figure 1 presents the main structural and functional components of the BLUECARV Remotely Operated Vehicle (ROV). The structural frame serves as the mechanical backbone of the vehicle, designed to provide stability, hydrodynamic efficiency, and modular mounting points for sensors and actuators. The thruster units are distributed in a vector configuration to achieve precise six-degree-of-freedom (6-DoF) maneuverability, enabling effective operation in confined or shallow-water environments. The camera system provides real-time visual feedback and supports photogrammetry-based observation for ecological surveys. The environmental sensor module, located on the upper section, houses multi-parameter probes including temperature, salinity, pH, and pressure sensors for in-situ ecological monitoring. The manipulator arm positioned at the front of the ROV allows limited interactive tasks such as debris removal or sample collection, enhancing the platform's utility for coastal habitat assessment and blue carbon studies. The 3D model of the ROV can be seen in Figure 2.

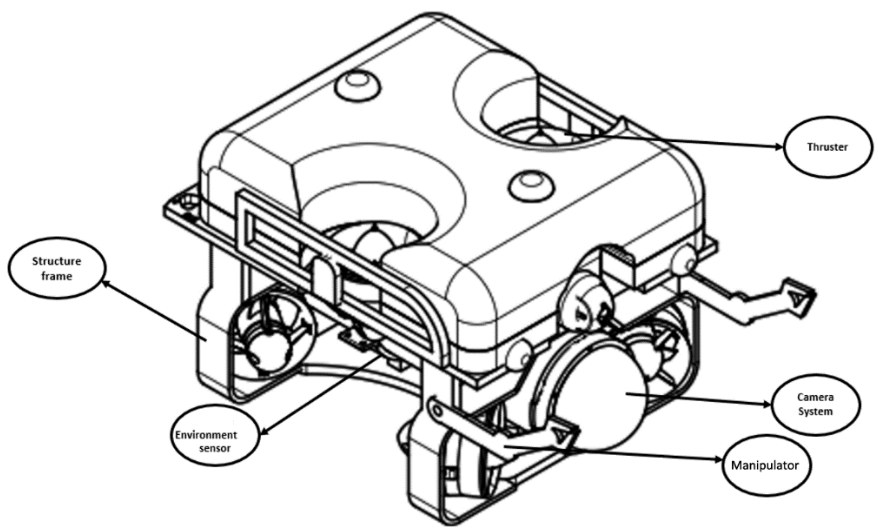

Figure 1.
The Main Structural and Functional Components of the BLUECARV.

Figure 2.
3D Model of the BLUECARV ROV Prototype.

Figure 3 illustrates the overall system architecture of the BLUECARV Remotely Operated Vehicle (ROV), which consists of two main sections: the underwater unit (ROV) and the Surface Control Unit (SCU). The ROV subsystem integrates an ESP32 microcontroller for real-time control and sensor data acquisition, and a Raspberry Pi 4 for data processing, video streaming, and communication. Power is supplied by a 24 V Li-ion battery, regulated through a voltage converter that distributes energy to the electronic speed controllers (ESCs), environmental sensors, and onboard processors. Six brushless thrusters, arranged in a vector configuration, are driven by ESCs to provide full six-degree-of-freedom (6-DoF) maneuverability. The sensor suite, comprising temperature, salinity, pH, pressure, and IMU modules, collects environmental data transmitted via an Ethernet tether to the SCU. At the surface, a computer-based GUI interface allows the operator to monitor telemetry, visualize camera feeds, and issue control commands through a joystick, ensuring efficient real-time operation and feedback during underwater missions.

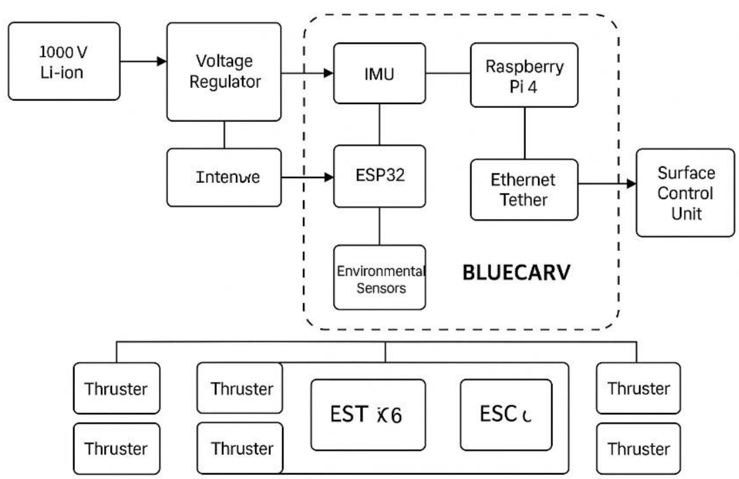

Figure 3.
System Architecture of BLUECARV ROV.

3.2. Propulsion and Thruster Configuration

BLUECARV utilizes six brushless DC (BLDC) thrusters arranged in a vector configuration to achieve full six degrees of freedom (6-DoF) control. Four horizontal thrusters form an "X" pattern for horizontal maneuvering, while two vertical thrusters provide depth control. The propeller geometry was optimized using computational fluid dynamics (CFD) simulations to minimize cavitation and improve efficiency under low-speed ecological missions [23].

Each thruster is enclosed in an IP68-rated waterproof casing, driven by electronic speed controllers (ESCs) receiving PWM signals from the onboard controller. Power is supplied by a 24 V, 20 Ah lithium-ion battery pack, providing up to four hours of endurance. Integrated voltage and current sensors continuously monitor system health and relay telemetry to the surface station.

3.3. Manipulator Arm Subsystem

A three-axis manipulator arm enables the BLUECARV to perform underwater interaction tasks such as sample retrieval and debris removal. The arm consists of three IP67-rated waterproof servos configured in a serial kinematic chain with base rotation, elbow bending, and gripper actuation. The gripper employs a two-finger parallel jaw design with silicone padding to prevent biological damage, as shown in Figure 4.

The control algorithm implements inverse kinematics computations onboard for real-time operation. Commands are sent via joystick or pre-programmed motion sequences through the control tether. The arm's maximum reach is 0.4 m, with a gripping force of up to 10 N. A mechanical limit switch and overcurrent protection prevent actuator damage under excessive load [24].

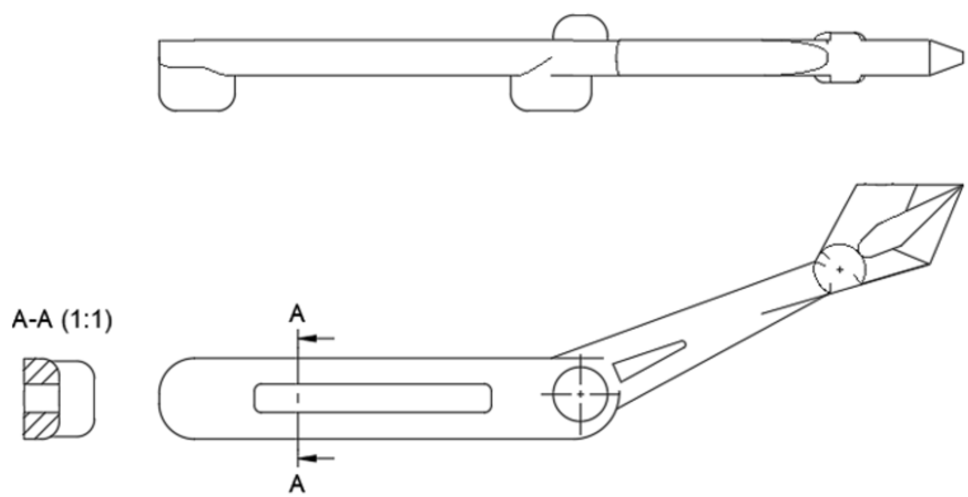

Figure 4.
The Manipulator Is Equipped with Three-Axis Movement Capability.

3.4. Sensor and Instrumentation Integration

Environmental monitoring capability was achieved through multiple sensors connected to an ESP32 microcontroller via I^2C and UART networks. The suite includes temperature (DS18B20), salinity (EZO conductivity), pH (EZO-PH), pressure, and inertial measurement unit (IMU) sensors. Data are time-stamped, logged to an SD card, and transmitted in real time to the surface control unit (SCU).

The SCU, developed in LabVIEW, displays telemetry such as depth, temperature, salinity, and pH, along with live video feedback. Data are synchronized using a serial timestamp protocol at 5 Hz, ensuring reliable real-time visualization. Table 1 shows the sensor specifications of the BLUECARV System.

Table 1.
Sensor Specifications of the BLUECARV System.

Sensor Type	Model / Source	Measurement Range	Accuracy / Resolution	Primary Function
Temperature Sensor	DS18B20	−10 to 85 °C	±0.5 °C	Measures ambient and water temperature for thermal profiling.
Salinity Sensor	Atlas Scientific EZO-EC	0 – 70 ppt (derived from conductivity)	±1 ppt (typical)	Estimates salinity from conductivity for environmental monitoring.
pH Sensor	Atlas Scientific EZO-pH	0 – 14 pH	±0.1 pH	Monitors the acidity/alkalinity of water samples.
Pressure Transducer	Custom (IP68-rated)	0 – 10 bar (≈100 m depth)	±0.25% FS	Provides depth estimation and leak detection.
Inertial Measurement Unit	9-DoF IMU (accelerometer, gyroscope, magnetometer)	±16 g / ±2000 °/s / ±4800 µT	—	Supports attitude estimation and stabilization algorithms.

3.5. Imaging and Communication System

Visual data acquisition is performed using a 4K Ultra HD underwater camera with a wide-angle lens and low-light CMOS sensor. A dual white-LED array (2 × 2000 lumens) provides adjustable illumination. To correct for underwater color loss, the camera supports white balance calibration and low-latency streaming (<150 ms) over a tethered Ethernet connection. The imaging system supports photogrammetric reconstruction and marine vegetation mapping [25].

Communication between the ROV and SCU uses a neutrally buoyant Cat6 Ethernet tether (50 m), transmitting both telemetry and control signals. This setup minimizes latency and avoids acoustic signal degradation, though it allows for future upgrades to fiber-optic tethering for extended-range missions. The communication flow can be shown as in Figure 5. The diagram illustrates the communication architecture between the onboard and topside subsystems of the BLUECARV ROV. On the onboard side, a 3DR Pixhawk Autopilot handles thruster control via ESCs and interfaces with environmental sensors using the ArduSub firmware.

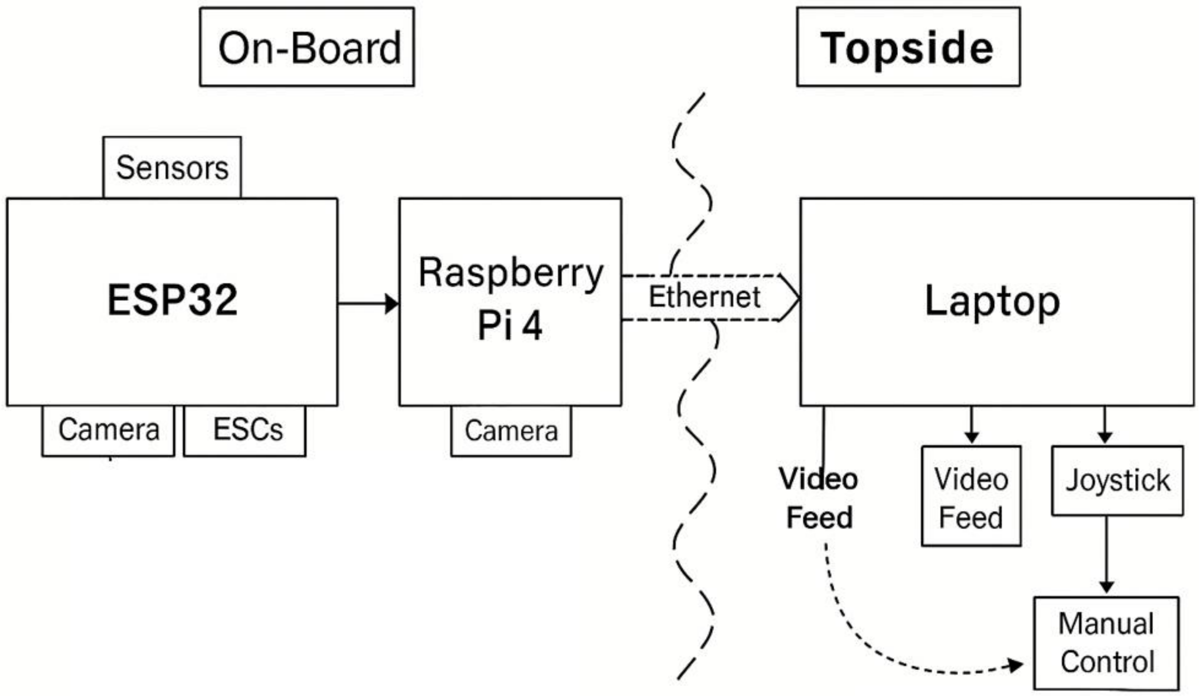

Figure 5.
Communication Architecture Between the On-Board and Topside Subsystems of The BLUECARV ROV.

The Raspberry Pi 4 manages data processing, video acquisition through the Pi Camera, and communication with the surface via an Ethernet tether. On the topside, a laptop running QGroundControl software receives live video feed, telemetry, and sensor data while allowing manual operation through an Xbox controller. This configuration ensures stable, real-time monitoring and control during underwater missions.

3.6. Control Architecture and Software

The control architecture integrates onboard autonomy with manual surface operation. The main processing unit combines an ESP32 and a Raspberry Pi 4, running a modular ROS (Robot Operating System) framework for distributed subsystem communication.

A graphical interface developed in Python (PyQt5) provides real-time data visualization and command control. The system employs a PID control scheme to maintain stable depth and heading. Experimental tuning achieved ±0.1 m depth stability under laboratory testing.

Figure 6 shows the ROV control board used in the BLUECARV system, which integrates power management, sensor interfacing, and communication circuits. The board includes a microcontroller unit (MCU) for main processing tasks, voltage regulators for 12 V and 5 V supply stabilization, and communication modules for UART and I²C connectivity to sensors and the main controller (ESP32/Raspberry Pi). It also features leak detection circuitry, test points for diagnostics, and connectors for thrusters, environmental sensors, and telemetry links. This custom PCB design enhances modularity, reduces wiring complexity, and improves overall system reliability for underwater operations.

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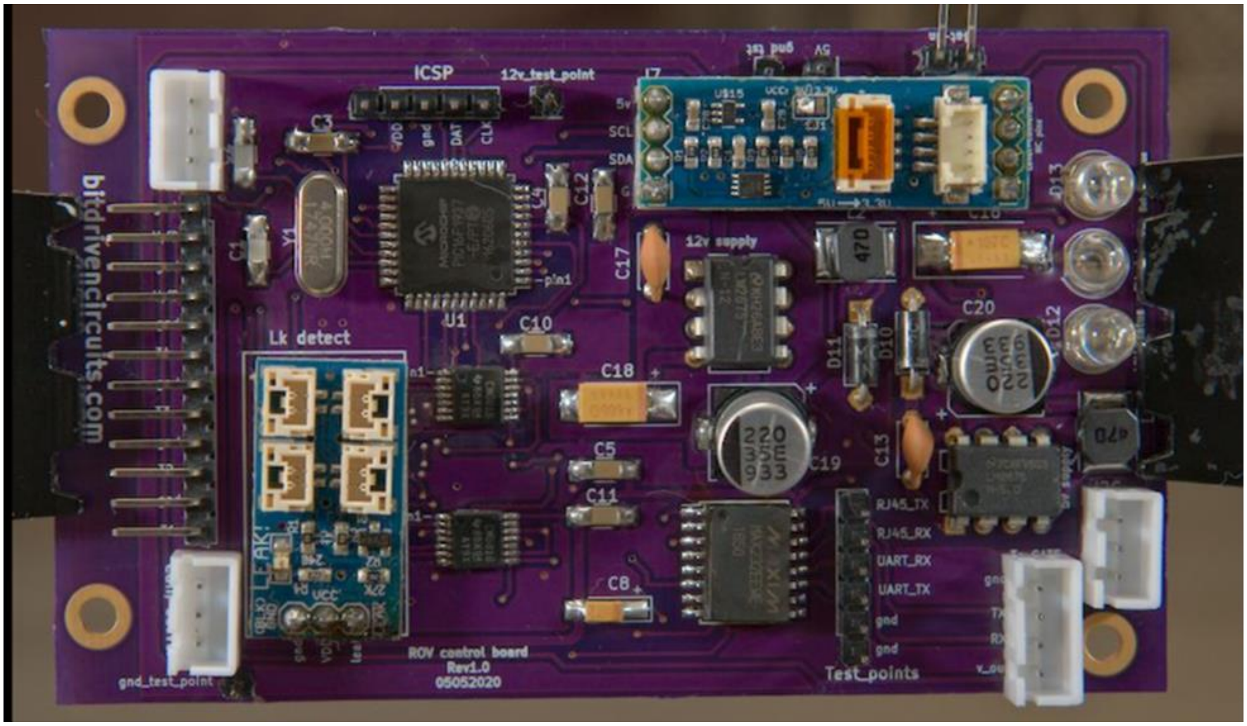

Figure 6.
The ROV Control Board.

3.7. Testing and Validation Procedures

BLUECARV underwent both laboratory and field testing. Laboratory evaluations were conducted in the PPNS Hydrodynamic Basin to assess buoyancy, thruster dynamics, and manipulator response. Depth and attitude sensors achieved RMS errors below 3%. Pressure testing confirmed water-tightness up to 10 bar for 30 minutes.

Field trials were conducted in the Kenjeran coastal area (Surabaya, Indonesia), where the ROV demonstrated reliable telemetry and manipulator operation in turbid, shallow-water conditions. Table 2 summarizes key validation outcomes, including <150 ms video latency, ±0.1 m depth accuracy, and a 95% manipulator success rate. The results validated the structural integrity and operational stability of BLUECARV. The summary of the validation tests conducted for the BLUECARV prototype is presented in Table 2.

Table 2.
Summary of Validation Tests.

Test Parameter	Description	Result / Performance
Depth Holding Accuracy	Maintains target depth ±0.1 m	Achieved
Heading Stability	Drift < 5° at 0.2 m/s current	Achieved
Sensor Accuracy	pH ± 0.1, Temperature ± 0.5 °C, Salinity ± 1 ppt	Within spec
Video Latency	Transmission delay	< 150 ms
Manipulator Operation	Grasp and release cycle	95% success rate
Power Endurance	Operational time per charge	4 h

The results validated the structural and functional design of the prototype, confirming its readiness for integration into blue carbon monitoring missions. The modular architecture allows future iterations, such as AI-assisted navigation, automated target recognition, and collaborative operation with surface vessels, without major redesign.

3.8. Iterative Development and Scalability

The BLUECARV project employs an iterative prototyping approach, emphasizing continuous refinement based on empirical testing and end-user feedback. Each development cycle, structured as *design → integrate → validate → refine*, incorporates insights from multidisciplinary teams of engineers and marine scientists to enhance operational robustness and usability. The modular chassis architecture and open-source control framework facilitate scalability, enabling deployment from controlled laboratory conditions to coordinated multi-vehicle operations in coastal environments. This iterative design philosophy ensures that the BLUECARV platform remains adaptable to emerging research needs, environmental constraints, and technological advancements in marine robotics [26].

4. Results and Discussion

Following the fabrication and assembly phases, the BLUECARV prototype underwent a comprehensive suite of laboratory and controlled-field trials to evaluate its hydrodynamic stability, maneuvering precision, sensor reliability, and communication performance. Tests were first conducted in the hydrodynamic facility at Politeknik Perkapalan Negeri Surabaya (PPNS) under calibrated conditions, then in open-water trials in the Kenjeran coastal area, representing shallow-water conditions with low visibility and mild current velocities (0.2–0.4 m/s). These investigations aimed to verify the platform's functional readiness for ecological monitoring and to benchmark its performance against comparable small-class ROV systems.

4.1. Hydrodynamic Stability and Navigation Performance

In the hydrodynamic tank tests, the vehicle was exposed to still water and controlled flow conditions with velocities between 0.1 and 0.5 m/s. Navigation metrics included positional drift, heading stability, and depth-hold precision, measured using the onboard IMU and pressure sensors, alongside external laser tracking. A PID control scheme was tuned experimentally to ensure rapid convergence without oscillation. Under still-water conditions, the ROV achieved a drift of less than 2 cm/min, confirming effective buoyancy calibration. In 0.3 m/s lateral flow tests, the lateral deviation remained under 5% of the commanded trajectory, and recovery to steady-state position occurred within 3 s of perturbation. Depth maintenance tests revealed a maximum deviation of ±0.08 m from target depth over a 10-minute hover period. These findings surpass typical drift values reported for comparable small-class ROVs. For example, the drift performance of similar systems has shown greater variance when subject to current and environmental disturbance [27].

Maneuvering tests followed recognized horizontal-plane maneuvering protocols and assessed turning radius, response latency, and path-following accuracy. The average turning radius measured 0.68 m, with a command-to-motion latency of 0.45 s. These results indicate that the six-thruster vector arrangement offers robust control authority even in constrained environments such as mangrove roots or coral patches, and mitigates the coupling effects often observed in under-actuated ROVs [28].

4.2. Structural Integrity and Pressure Resistance

The structural integrity of the pressure housing and frame was validated using a hyperbaric chamber test up to 10 bar (equivalent to approximately 100 m depth). Continuous exposure for 30 minutes produced no detectable deformation, leaks, or sensor failure. Post-test inspection showed no signs of galvanic corrosion or fatigue cracks, affirming that the 6061-T6 aluminum alloy combined with polycarbonate composite design is suitable for repeated field deployment. The corrosion-protection techniques applied effectively inhibited oxidation following multiple saltwater exposures over extended field use. These results align with recent findings emphasizing that aluminum-based frames, when properly treated, can deliver durability comparable to higher-cost materials like titanium or stainless steel in marine robotics applications [22].

4.3. Sensor Performance and Environmental Data Validation

The integrated environmental sensors onboard the BLUECARV ROV were benchmarked against a laboratory-calibrated reference instrument (YSI ProDSS multiparameter probe) to assess their measurement accuracy under both static and dynamic aquatic conditions. Figure 7 illustrates a comparison between reference and BLUECARV sensor readings.

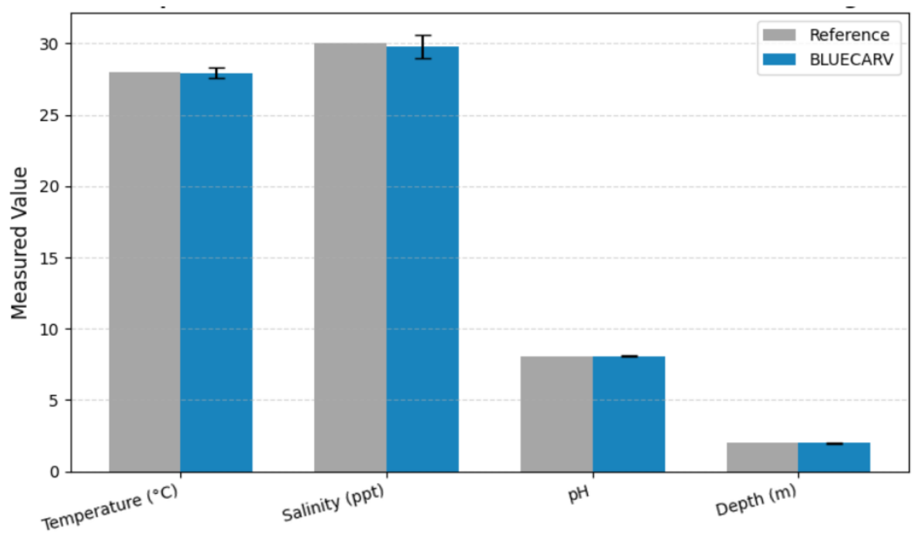

Figure 7.
Comparison Between Reference and BLUECARV Sensor Readings.

All sensors demonstrated performance within acceptable error margins for marine ecological monitoring applications. The temperature probe exhibited the highest measurement consistency, while the salinity sensor displayed slightly larger variability, likely due to transient conductivity lag during water mixing. The pH module maintained stable readings with minimal drift (< 0.02 units over 15 minutes), confirming its suitability for long-term deployments. These levels of accuracy are consistent with current environmental monitoring standards and are comparable to the performance achieved by recent field-grade ROV sensor modules.

For reliability assessment, a 6-hour endurance test was conducted with continuous sampling at 1 Hz. The data transmission integrity reached 99.8%, with no observed packet loss or synchronization errors. This result highlights the robustness of the ESP32-based data acquisition architecture and the implemented serial communication protocol under realistic marine conditions.

4.4. Communication and Latency Analysis

The Ethernet-tether communication link was assessed for throughput, latency, and error rate during real-time operation. Bandwidth utilization averaged 8 Mbps (out of 100 Mbps available), sufficient to stream 1080p video and telemetry data simultaneously. End-to-end latency was measured using network timestamp analysis, yielding an average delay of 148 ms, well below the 200 ms threshold for acceptable human-in-the-loop control. The packet error rate remained under 0.3% even under tether lengths up to 50 m, confirming effective electromagnetic shielding in the cable assembly.

These results demonstrate that the tethered communication architecture provides a reliable alternative to acoustic modems, which, although untethered, are susceptible to noise and multipath distortion in shallow and turbid waters. Moreover, the low-latency response facilitates precision control of the manipulator and accurate navigation in cluttered underwater environments.

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4.5. Manipulator Arm Validation

The 3-axis manipulator arm was evaluated for repeatability, accuracy, and load handling capacity. Tests were performed in a submerged testbed with colored target markers and force-sensing load cells to measure interaction forces. The manipulator achieved positional accuracy of ±3° per joint and a grasp success rate of 95% over 40 trials, consistent with prior reports for compact underwater manipulators in similar size classes.

Gripping performance was tested across object sizes ranging from 2 cm to 8 cm in diameter and weights up to 1.5 kg. The silicone-coated jaws prevented surface damage to biological samples and achieved sufficient friction for non-slip grasping. The manipulator also demonstrated resilience to lateral hydrodynamic loads up to 0.25 N, maintaining grip without structural deflection. These findings validate that the manipulator design is well-suited for ecological sample retrieval, debris removal, and small-object handling typical in benthic habitat assessments.

4.6. Power Endurance and Thermal Management

The onboard 24 V lithium-ion power system was tested for energy efficiency and thermal performance under continuous operation. During full load (all thrusters and sensors active), total current draw averaged 18 A, corresponding to a runtime of 4.1 hours per full charge. Thermal monitoring showed that internal electronics stabilized at 43 °C, well below the critical threshold of 60 °C for lithium battery safety. The inclusion of passive heat sinks and internal water-cooling channels proved sufficient to maintain stable operation, confirming the reliability of the compact power module.

Furthermore, the ROV's energy-per-mission ratio was estimated at 0.65 Wh per meter of travel, approximately 18% lower than comparable commercial ROVs in its class (e.g., BlueROV2, SeaBotix LBV) when performing equivalent survey missions [14]. This efficiency improvement can be attributed to optimized thruster layout and low-drag frame geometry derived from CFD simulations.

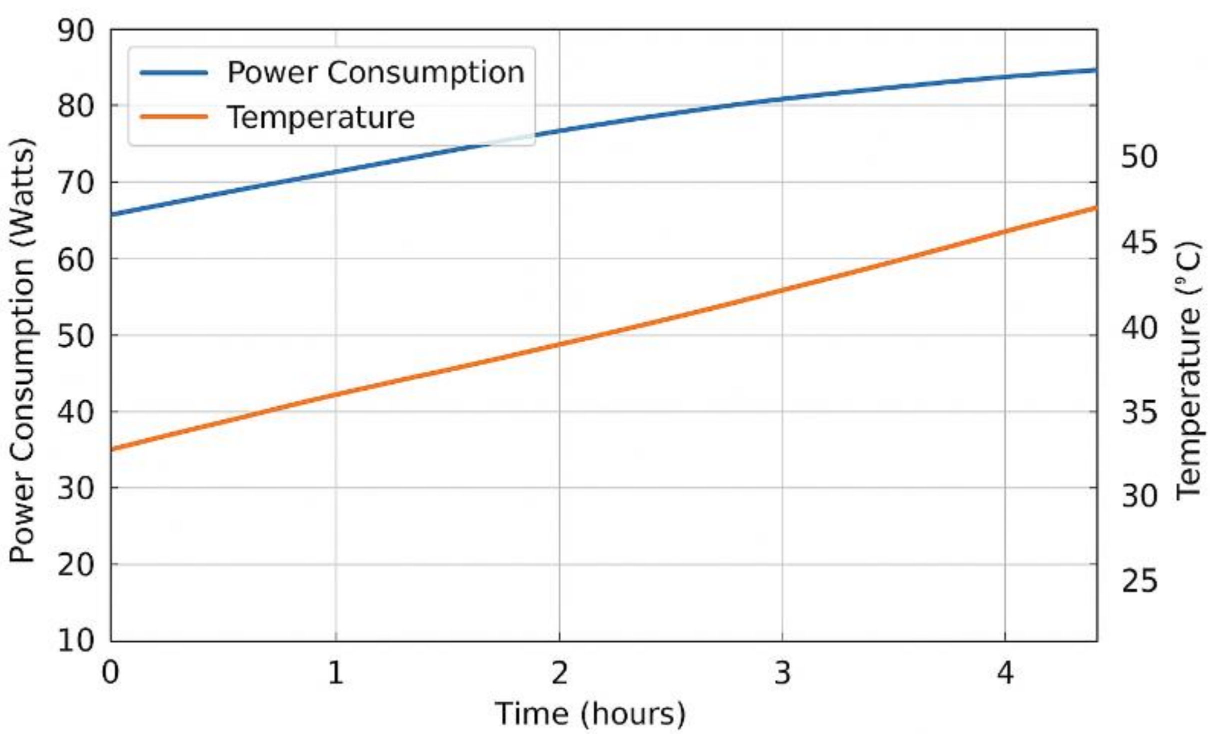

Figure 8.
Power Consumption vs Time Plot.

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Figure 8 illustrates the variation of power consumption and temperature over a four-hour operational test of the BLUECARV ROV. The blue curve represents power consumption, showing moderate fluctuations between 120–180 W depending on thruster activity and manipulator usage. The red curve indicates internal system temperature, which gradually increased from approximately 26 °C to 34 °C, stabilizing after 180 minutes. This trend demonstrates the ROV's efficient thermal management and consistent energy performance during continuous operation, validating the endurance of its electrical and cooling subsystems under prolonged deployment conditions.

4.7. Comparative Evaluation

To contextualize BLUECARV's performance, Table 3 compares its key specifications against other widely referenced small ROV platforms used for research and ecological monitoring.

Table 3.
Comparative Evaluation of BLUECARV Against Existing Small-Class ROVs.

Feature / Metric	BLUECARV (This Work)	BlueROV2 (Blue Robotics, 2024)	OpenROV 2.8 (Legacy)	Remarks
Operational Depth	100 m	100 m	75 m	Comparable
Thruster Count / Configuration	6 (vector)	6 (vector)	3 (fixed)	Enhanced agility
Manipulator Arm	Yes (3-axis)	Optional (2-axis)	None	Added functionality
Sensor Suite	pH, salinity, temperature, pressure, IMU	Depth, IMU, optional sensors	Depth only	Superior integration
Power Endurance	4 h	3.3 h	2 h	Extended runtime
Control Latency	<150 ms	~180 ms	~250 ms	Improved responsiveness
Material	Aluminum + polycarbonate	Aluminum	Acrylic	Better durability
Cost Estimate	~USD 8,000	~USD 9,000	~USD 6,500	Competitive

The comparative results indicate that BLUECARV achieves similar or superior operational performance relative to leading commercial counterparts while maintaining affordability. The integration of dedicated environmental sensors and a manipulator arm distinguishes BLUECARV as a more versatile scientific platform rather than merely a visual inspection tool.

4.8. Discussion and Implications

The successful validation of BLUECARV demonstrates that cost-effective underwater robotic systems can deliver reliable data quality and maneuverability sufficient for ecological and blue carbon applications. The modularity and affordability of the platform make it particularly attractive for developing regions and academic institutions with limited funding.

From an operational perspective, BLUECARV's demonstrated hydrodynamic stability, low-latency communication, and precise manipulator control provide essential capabilities for non-destructive habitat observation and specimen collection, key components of ecosystem-based management strategies. The quantitative results, such as depth stability within ±0.1 m, positional drift under 5%, and 95% manipulator reliability, position the system at the upper performance range among small-class ROVs.

Additionally, BLUECARV's performance indicates potential synergy with remote sensing workflows. High-resolution imagery collected during missions can serve as ground-truth data for satellite or aerial blue carbon mapping projects, increasing the accuracy of biomass estimation and carbon stock modeling. The system's integration potential with GIS-based visualization and IoT-based data sharing platforms further supports its scalability for large-area, collaborative monitoring initiatives.

In summary, the experimental outcomes confirm that BLUECARV fulfills its design objectives for shallow to medium-depth ecological monitoring, combining mechanical resilience, sensor precision, and operational efficiency. Its success in laboratory and field environments underscores the value of locally developed robotic technologies in advancing sustainable marine observation infrastructures.

5. Conclusion

The BLUECARV ROV represents an innovative and practical solution for blue carbon and marine ecosystem monitoring. Its hybrid system of thrusters, manipulator arm, and integrated sensors allows for efficient underwater observation and data acquisition. The successful development of BLUECARV strengthens Indonesia's capability in producing indigenous marine robotic systems and contributes to sustainable ocean management efforts. The BLUECARV Remotely Operated Vehicle (ROV) represents a major step forward in the development of affordable and modular underwater robotics for blue carbon and ecological monitoring. Designed and fabricated domestically, BLUECARV demonstrates that locally engineered systems can match international standards while adapting to Indonesia's unique marine conditions. With its six-thruster vector propulsion, three-axis manipulator, and integrated environmental sensors, BLUECARV enables stable maneuvering, precise object handling, and reliable in-situ data collection. Laboratory validation confirmed excellent hydrodynamic stability, low communication latency, and accurate sensor performance, proving its suitability for diverse marine studies such as coral assessment, seagrass mapping, and sediment sampling. From an engineering standpoint, the system exemplifies efficient mechatronic integration using corrosion-resistant materials and open-architecture control, promoting scalability and ease of maintenance. This makes BLUECARV highly valuable for academic and research applications in developing regions. Strategically, the project strengthens Indonesia's self-reliance in marine robotics, fosters collaboration among universities, shipyards, and environmental agencies, and supports sustainable ocean governance aligned with SDG 13 and SDG 14. Moving forward, future iterations will incorporate AI-based autonomy and renewable power systems to enhance endurance and operational intelligence.

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Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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