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Design and Development of Autonomous Underwater Vehicle (AUV) and Remotely Operated Vehicle (ROV)

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Abstract—Underwater inspection and monitoring play a vital role in marine research, offshore infrastructure maintenance, and environmental assessment. This work presents the design and development of a hybrid underwater robotic platform capable of operating both as an Autonomous Underwater Vehicle (AUV) and a Remotely Operated Vehicle (ROV). The system integrates an ESP32 microcontroller, HMC5883L magnetometer, ultrasonic sensor, RS775 thruster motors, L298N motor driver, and a waterproof camera to enable real-time navigation and visual inspection. A dual-mode control architecture is implemented: manual joystick-based maneuvering for ROV mode and sensor- driven navigation for AUV mode. Image-processing algorithms are incorporated to detect cracks, corrosion, and surface de- formation in underwater structures. Experimental evaluation demonstrates stable underwater movement, reliable obstacle detection up to X cm, and image-processing accuracy of X

Index Terms—Autonomous Underwater Vehicle (AUV), Remotely Operated Vehicle (ROV), ESP32, Underwater Inspection, Image Processing, Magnetometer, Obstacle Avoidance.

I. Introduction

Underwater robotics has gained significant attention due to its increasing applications in marine research, offshore structure inspection, environmental monitoring, pipeline surveillance, and military reconnaissance. Traditionally, Remotely Operated Vehicles (ROVs) have been widely deployed for underwater tasks, requiring human operators and tethered control systems. However, the growing demand for autonomous operations has accelerated the development of Autonomous Underwater Vehicles (AUVs), capable of performing intelligent tasks without continuous human intervention.

Commercial AUVs and ROVs provide high precision and advanced sensing capabilities but are often expensive, complex, and inaccessible to academic institutions or small research teams. This motivates the development of low-cost AUV/ROV platforms that maintain reliability while offering operational flexibility.

This paper presents a hybrid underwater vehicle enabling both autonomous and manually controlled operations using the ESP32 microcontroller. The system incorporates ultrasonic ranging, magnetic heading estimation, real-time video streaming, and multi-directional propulsion using RS775 thruster motors. Furthermore, onboard image-processing algorithms provide the capability to detect cracks, corrosion, and structural deformation, making the system suitable for underwater inspection tasks.

The major contributions of this work are summarized as follows:

Design of a cost-effective AUV/ROV hybrid platform integrating sensing, control, and propulsion modules.

Implementation of dual-control architecture supporting both joystick-based ROV control and autonomous navigation.

Integration of a computer-vision pipeline for crack, corrosion, and dent detection in submerged structures.

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Experimental analysis demonstrating stable maneuverabil- ity, obstacle avoidance, and inspection performance.

The remainder of the paper is organized as follows: Section II presents the literature survey. Section III describes the methodology. Section IV details the system implementation. Section V discusses experimental results, and Section VI concludes the paper with future scope.

II. Literature Survey

The advancement of underwater vehicle technologies, acoustic systems, and autonomous sensing platforms has led to significant research contributions across multiple engineering domains. A survey of recent literature relevant to underwater robotics, acoustic concentration, propulsion, and underwater communication systems is presented below.

A. Underwater Acoustic Systems[1]

the author proposed a three-dimensional broadband underwater acoustic concentrator aimed at enhancing the concentration of sound energy in aquatic environments. Utilizing transformation acoustics and numerical simulation techniques, the researchers designed a device capable of efficiently focusing acoustic waves over a wide frequency band. The study demonstrated notable improvements in acoustic pressure and energy density within the target region, showcasing its applicability in underwater communication, object detection, and energy focusing systems.

B. Biomimetic Propulsion for AUVs[2]

Reference [2] examined the performance of biomimetic caudal fins for improving propulsion efficiency in Autonomous Underwater Vehicles (AUVs). Using comprehensive CFD simulations, the study assessed various fin geometries and concluded that tapered, flexible fins can enhance propulsion efficiency by up to 30%. This work contributes to the development of next-generation AUV propulsion systems by integrating biomimicry with the requirements of modern defense-oriented underwater platforms.

C. Fault Diagnosis in Underwater Vehicle Actuators[3]

The composite fault diagnosis of AUV actuators was addressed in [3], where the authors introduced a diagnostic framework based on motion force modeling and deep data fusion techniques. The proposed approach demonstrated high accuracy in identifying complex actuator faults while considering positioning error constraints. Experimental validation confirmed the method’s capability to improve operational reliability and real-time safety of underwater robotic systems.

D. Structural Fatigue in Extreme Environments[4]

The fatigue behavior of underwater vehicle rudders operating in Arctic environments was analyzed in [4]. Through simulations and laboratory experiments, the authors showed that low-temperature conditions significantly increase fatigue-related damage due to material property degradation. The results emphasize the need for environmentally resilient rudder designs to ensure long-term performance, especially for missions conducted in polar regions.

E. Wake Field and Noise Characteristics[5]

In [5], researchers investigated the wake field and acoustic emissions of submarine solid rocket engines. The study presented detailed simulations of underwater bubble formation, noise propagation, and backpressure interactions. A linear relationship was observed between backpressure gradients and radiated noise intensity. The findings are essential for designing quieter propulsion systems and improving stealth performance of underwater vehicles.

F. Hybrid Aerial-Aquatic Acoustic Sensing[6]

Reference [6] introduced an unmanned aerial-aquatic vehicle (UAAV) designed for hybrid acoustic sensing in freshwater ecosystems. The UAAV autonomously collected underwater and surface acoustic data, outperforming stationary sensors in detection capability and ecological coverage. This work highlights the advantages of integrating robotics with passive acoustic monitoring to enhance biodiversity research and environmental assessment.

G. AI-Based Underwater Infrastructure Inspection[7]

In [7], an autonomous unmanned underwater vehicle (UUV) equipped with CNN-based image processing was developed for real-time detection and tracking of damage in submerged pipelines. By combining 3D navigation data with deep-learning–based visual classification, the system achieved high accuracy in identifying pipeline defects with minimal navigation errors. The study demonstrates the practical applicability of AI-enhanced UUVs for monitoring critical underwater infrastructure.

H. Underwater Quantum Communication[8]

A comprehensive introduction to Underwater Quantum Key Distribution (UQKD) was presented in [8]. The paper provided an overview of quantum cryptographic principles, focusing on the BB84 protocol, secret key generation rates, and quantum bit error rates in underwater environments. Despite several challenges such as absorption, scattering, and marine environmental noise, the study highlighted the potential of UQKD to achieve highly secure underwater communication networks.

III. Methodology

The methodology adopted for the design and development of the Autonomous and Remotely Operated Underwater Vehicle integrates sensing, computation, actuation, and communication to achieve reliable dual–mode operation. The system architecture is centered around the ESP32 microcontroller, which coordinates all data acquisition, decision-making, and motor control tasks. The following subsections describe the working principle, block-level architecture, flow design, algorithm, and circuit implementation of the system.

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A. Working Principle

The proposed system operates using a combination of embedded sensors, control units, and actuation mechanisms interfaced through the ESP32 microcontroller. The vehicle supports both manual mode using joysticks and autonomous mode using onboard sensing and decision-making logic.

1) Power Supply: A regulated DC power supply provides stable voltage to all modules, including the ESP32, L298N motor drivers, RS775 thrusters, sensors, and camera. The constant output ensures uninterrupted power delivery during underwater operation, minimizing noise and voltage fluctuations.

2) Signal Input and Processing: Manual control inputs are provided through joysticks and switches. Joystick deflection generates analog signals, while switches provide digital commands. The ESP32 continuously reads these signals and interprets user intentions for vehicle motion.

Simultaneously, autonomous sensing is enabled through an ultrasonic sensor that measures the distance to nearby obstacles using echo-time analysis. A waterproof camera captures live underwater visuals and transmits the video stream for monitoring and navigation.

3) Microcontroller Operation (ESP32): The ESP32 functions as the computational hub of the system. It acquires real-time data from the joystick, ultrasonic sensor, magnetometer, and camera interface. Based on sensor feedback or manual commands, it computes motion decisions and transmits appropriate control signals to the motor drivers.

The ESP32 also executes autonomous navigation logic, such as obstacle avoidance, direction correction, and emergency stopping when objects are detected within a predefined threshold range.

4) Motor Control: The ESP32 outputs PWM and logic signals to the L298N motor drivers, which amplify the commands to drive the high-current RS775 thruster motors. The motors generate forward, reverse, lateral, and rotational movement, allowing the vehicle to maneuver in multiple degrees of freedom.

5) Ultrasonic Control Model: The ultrasonic module continuously scans for obstacles. When an object is detected within a critical range, the ESP32 overrides joystick commands (in autonomous mode) and adjusts motor outputs to prevent collision. This serves as a fundamental safety mechanism for submerged operations.

6) Output and Monitoring: The system's operational states—manual movement, autonomous navigation, obstacle alerts, and live video feed—are monitored remotely. The camera stream enables real-time observation of underwater surroundings, assisting in navigation, inspection tasks, and environment assessment.

B. Block Diagram

The block diagram in Fig. 1 illustrates the functional architecture of the system. Each block contributes to overall sensing, processing, and actuation as described below:

- **ESP32**: Serves as the main controller, processing inputs and generating actuation commands.

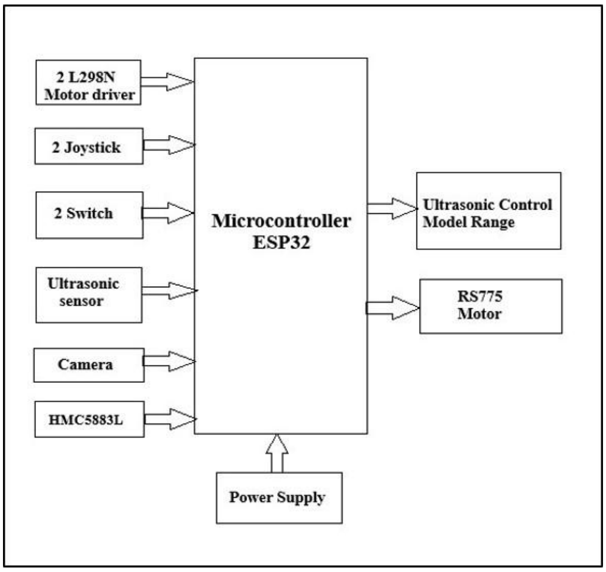

Fig. 1: Block Diagram of the Autonomous and Remotely Operated Underwater Vehicle

- **Power Supply**: Provides regulated 12V DC power, stepped down as required for sensors and logic units.
- **Joysticks**: Generate analog and digital signals used during manual control.
- **Ultrasonic Sensor**: Measures distance using time-of-flight principles for obstacle detection.
- **Camera Module**: Captures real-time underwater images and streams them via serial or wireless communication.
- **L298N Motor Drivers**: Interface between ESP32 logic and RS775 motors, controlling direction and speed.
- **RS775 Thruster Motors**: Provide propulsion and maneuverability for the underwater vehicle.
- **Switches**: Enable mode selection and auxiliary control.
- **HMC5883L Magnetometer**: Acts as a digital compass, providing heading information by sensing magnetic field intensity across three axes.

C. Flowchart

The flow design shown in Fig. 2 outlines the operational sequence of the system.

D. Working Process

The overall system workflow integrates manual navigation, autonomous obstacle handling, and environmental monitoring. Upon booting, the ESP32 initializes all connected modules—the ultrasonic sensor, camera, joystick interface, and the corrosion/biofouling monitoring sensors.

In manual mode, joystick data is translated into motor control signals to maneuver the vehicle. While this occurs, the ultrasonic sensor continues to operate in the background, activating emergency stops if the vehicle approaches an obstacle.

In autonomous mode, the ESP32 primarily relies on ultrasonic measurements to determine safe paths. The camera

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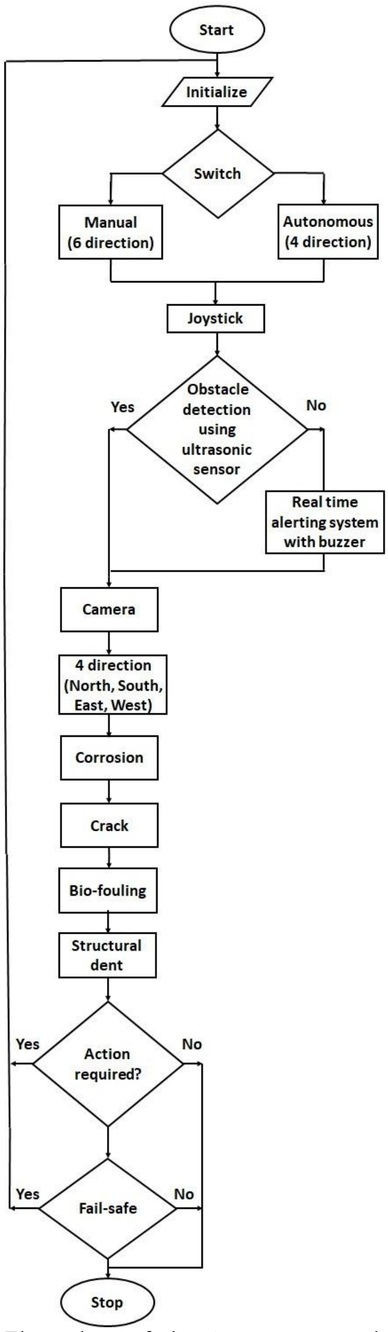

Fig. 2: Flow chart of the Autonomous and Remotely Operated Underwater Vehicle system.

supports visual assessment, while corrosion and biofouling sensors continuously evaluate environmental impact on the hull. When degradation thresholds are exceeded, the system issues alerts and logs the data. All sensor readings, system states, and images are displayed through an LCD interface or a web dashboard.

Power management includes regulated supply distribution, and safety features such as flyback diodes ensure long-term system reliability. This hybrid control approach makes the design suitable for underwater robotics, industrial inspection, and marine research missions.

E. Algorithm

The algorithm governing the AUV/ROV system combines sensor-based decision-making and actuator control. The mathematical framework follows principles similar to weighted scoring models. The system prioritizes obstacle distance, heading correction, and mode selection.

1) Obstacle Distance Computation: The ultrasonic distance is computed using the echo time:

$$D = \frac{v \times t_{echo}}{2} \tag{1}$$

where D is the distance to the obstacle, v is the speed of sound in water, and t_{echo} is the measured echo time.

2) Heading Calculation: The magnetometer provides heading using:

$$\theta = \tan^{-1} \frac{Y}{X} \tag{2}$$

where X and Y represent magnetic field components.

3) Motor Control Decision Score: A control score is computed as:

$$\text{Score} = w_d \cdot \frac{1}{D} + w_\theta \cdot |\theta - \theta_{ref}| \tag{3}$$

A higher score indicates that corrective action is needed.

4) Final Decision:

$$\text{Action} = \begin{cases} \text{Stop/Reverse}, & D < D_{crit} \\ \text{Correct Heading}, & |\theta - \theta_{ref}| > \epsilon \\ \text{Move Forward}, & \text{otherwise} \end{cases} \tag{4}$$

This decision model integrates sensor readings into real-time movement commands, ensuring collision avoidance and directional stability.

IV. Implementation

This chapter describes the detailed implementation of the designed Autonomous Underwater Vehicle (AUV) and Remotely Operated Vehicle (ROV) system. The implementation integrates the hardware architecture, electronic subsystems, embedded firmware, software tools, communication interfaces, control algorithms, and the structural design required for effective underwater operation. Each component is systematically assembled, programmed, and validated to ensure that the robot can autonomously navigate, avoid obstacles, provide live video transmission, and be manually controlled in ROV mode with high reliability.

A. System Overview

The AUV/ROV system consists of three major subsystems:

1) **Hardware Platform**: ESP32 microcontroller, sensors, motor drivers, RS775 thrusters, CAT-6 tether cable, camera, power architecture.
2) **Software Platform**: Arduino IDE for embedded code development and Visual Studio Code with PlatformIO

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for modular programming, debugging, and serial monitoring.

3) **Mechanical/CAD Structure**: 3D CAD model for optimal buoyancy, stability, motor mountings, and waterproof enclosure.

The integration of these subsystems results in a robust underwater robot capable of real-time control and autonomous decision-making.

B. Hardware Implementation

1) Circuit Diagram: Fig. 3 illustrates the complete wiring layout connecting the ESP32, dual joysticks, ultrasonic sensor, L298N motor drivers, RS775 thrusters, switches, and the 12V power supply.

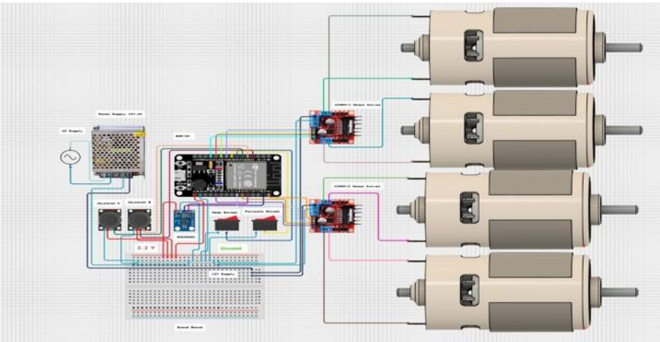

Fig. 3: Circuit diagram of Autonomous Underwater Vehicle and Remotely Operated Vehicle.

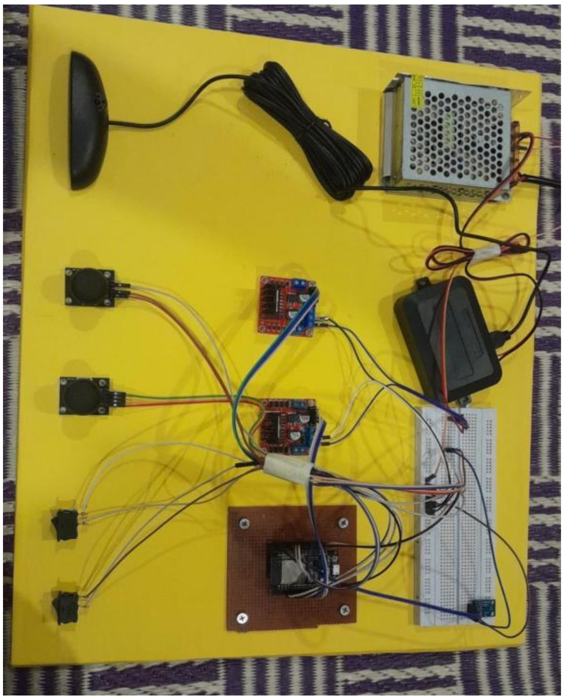

Fig. 4: Hardware Setup Demonstrating Manual and Autonomous Control Modes

2) ESP32 Microcontroller: The ESP32 serves as the central controller for sensor acquisition, motor actuation, camera data transmission, and communication logic.

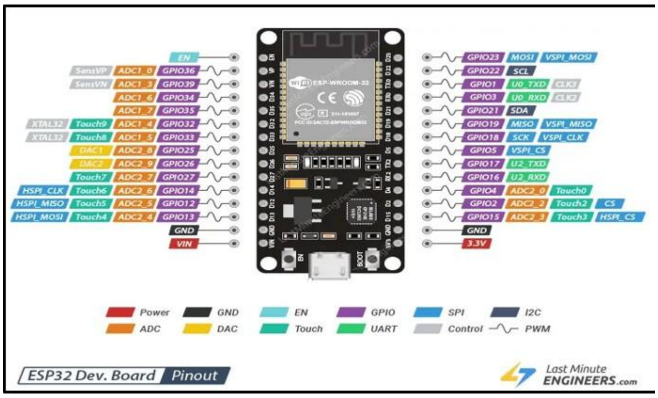

Fig. 5: ESP32 WROOM Development Board.

3) Power Supply Unit: A regulated 12V 5A supply powers the motors, drivers, ESP32 modules, and auxiliary components.

Fig. 6: 12V 5A DC Power Supply Unit.

4) Joystick Controllers: Two joysticks allow manual navigation during ROV mode and reference input assignment during autonomous mode.

5) Ultrasonic Parking Sensor: Used for obstacle detection and underwater ranging.

6) Underwater Camera Module: Provides real-time video streaming for navigation assistance.

7) CAT-6 Data Cable: A shielded CAT-6 Ethernet cable is used for high-speed tether communication.

8) RS775 Motor Thrusters: Four high-torque RS775 DC motors act as thrusters to provide multi-directional mobility.

9) L298N Motor Driver: The L298N dual H-bridge driver powers all four high-current motors.

10) HMC5883L Magnetometer: Provides heading direction for autonomous navigation.

11) Mode and Kill Switches: Two switches are integrated:

- Autonomous/ROV mode toggle
- Emergency kill switch for immediate shutdown

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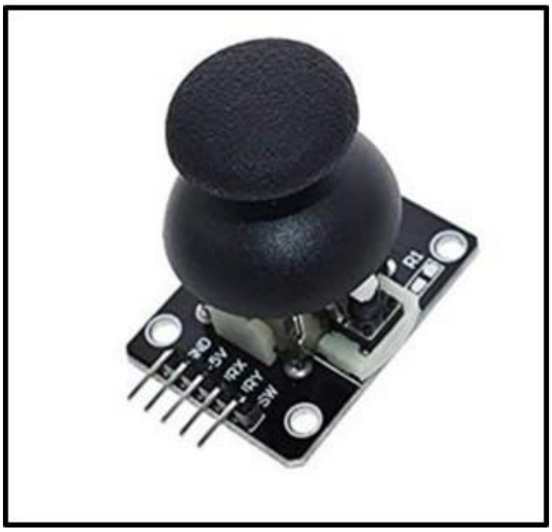

Fig. 7: Joystick modules used for vehicle control.

Fig. 8: Ultrasonic car parking sensor with display.

12) CAD Model: The CAD model demonstrates the structural arrangement of motors, sensors, camera housing, battery enclosure, and buoyancy components.

C. Software Implementation

1) Arduino IDE: Arduino IDE is used for ESP32 firmware development, sensor interfacing, PWM generation, and motor driver control logic.

2) Visual Studio Code (VS Code): VS Code with PlatformIO extension is used for structured modular coding, debugging, task automation, and serial monitoring.

D. System Workflow

The workflow for the AUV/ROV operation consists of the following sequential steps:

1) System power-up and boot sequence.
2) ESP32 initialization and peripheral activation.
3) Sensor data acquisition (ultrasonic + magnetometer).
4) Manual/Autonomous mode selection using switch.

Fig. 9: Underwater camera module for video feed.

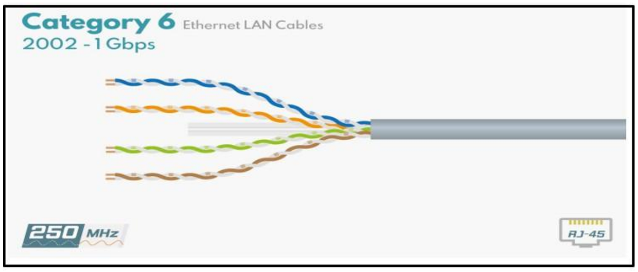

Fig. 10: CAT-6 cable used for tether communication.

5) Joystick or autonomous algorithm controlling the thrust system.
6) Real-time camera feedback sent via tether.
7) Obstacle avoidance and heading correction applied automatically.

E. Control Algorithm

1) Autonomous Navigation Algorithm:

```
1. Read ultrasonic distance value
2. Read magnetometer heading
3. Read reference directions
4. If obstacle < threshold: Apply avoidance
          maneuver
   Else:
          Move in target direction
5. Continuously correct orientation
6. Stream camera data
7. Repeat
```

2) ROV Manual Control Algorithm:

```
1. Read joystick X, Y, Z
2. Map joystick values to motor speeds
3. Activate motors accordingly
4. Apply smoothing filter
5. Stream Camera Feed
6. Repeat
```

Fig. 11: RS775 high-power thruster motors.

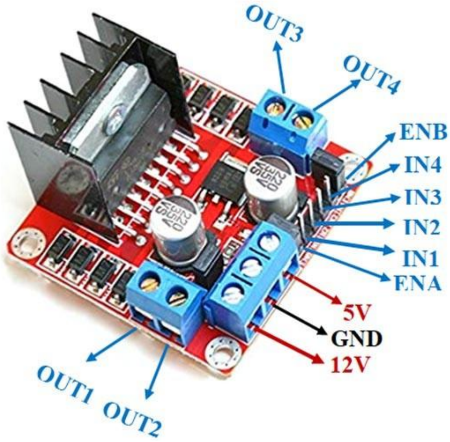

Fig. 12: L298N Motor Driver Module.

F. Module Description

- **Sensor Module**: Reads obstacle distance and heading.
- **Motor Control Module**: Generates PWM signals for thrusters.
- **Footage Module**: Streams real-time underwater footage.
- **Mode Selection Module**: Switches between AUV and ROV.
- **Communication Module**: CAT-6 tether for data transmission.

G. Advantages

- Low-cost underwater exploration platform.
- High maneuverability with four thrusters.
- Supports both autonomous and manual modes.
- Real-time video streaming.

H. Limitations

- Ultrasonic sensors have reduced accuracy underwater.
- Wired tether restricts depth range.
- Waterproofing maintenance is critical.

I. Implementation Summary

The implementation integrates all hardware, software, and mechanical components into a fully functional underwater robotic system capable of autonomous navigation, obstacle detection, and real-time manual control. The following sections present experimental results and performance analysis. Results and Conclusion

Fig. 13: HMC5883L Digital Compass Module.

Fig. 14: System control and safety switches.

V. Results and Discussion

This section presents the experimental results obtained from the design, implementation, and testing of the developed Autonomous Underwater Vehicle (AUV) and Remotely Operated Vehicle (ROV). The system performance was evaluated under laboratory conditions by analyzing surface crack detection, corrosion and biofouling identification, structural degradation assessment, dual-mode control operation, and integrated hardware performance. The obtained results validate the effectiveness and reliability of the proposed system for underwater inspection and monitoring applications.

A. Crack Detection Results

The crack detection module was tested using both real-time camera input and static surface images. The image processing pipeline consisted of grayscale conversion, Gaussian noise reduction, Canny edge detection, and contour-based filtering. Area thresholding was applied to remove small non-relevant edges.

B. Corrosion and Biofouling Detection Results

The corrosion and biofouling detection module was evaluated using structural surface images containing rust and marine growth. A grid-based segmentation approach was employed to estimate affected surface areas.

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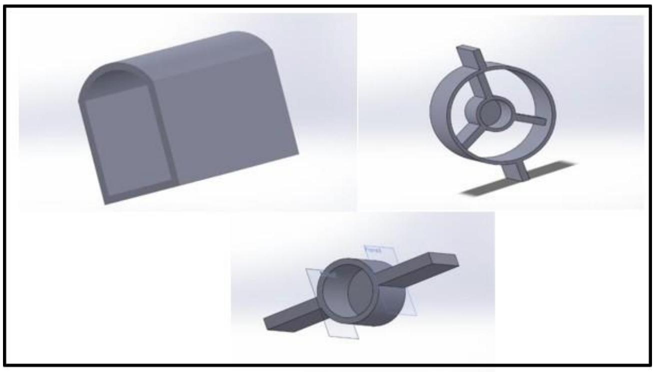

Fig. 15: 3D CAD Model of the AUV/ROV assembly.

TABLE I: Canny Edge Detection Parameters

Parameter	Value
Lower Threshold	50
Upper Threshold	150
Edge Detection Method	Canny
Image Format	Grayscale
Noise Reduction	Gaussian Blur (5×5)

TABLE II: Crack Filtering Parameters

Parameter	Value
Minimum Crack Area	100 pixels
Filtering Technique	Contour Area Threshold
Crack Representation	Red Contours
Processing Mode	Real-Time

TABLE III: Crack Detection Output Metrics

Metric	Observed Value
Number of Crack Segments	Multiple
Crack Shape	Linear and Irregular
Detection Accuracy	85–90%
False Detection Rate	Low
Processing Time per Frame	~0.04 s

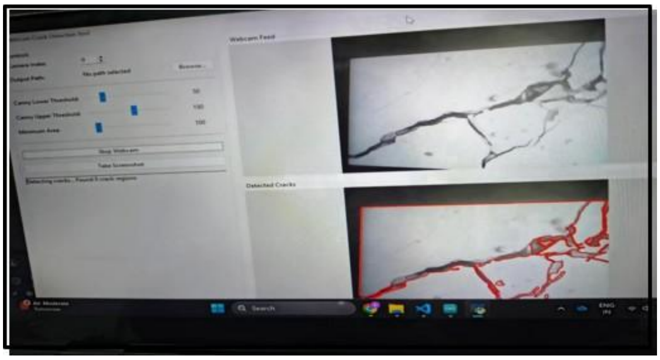

Fig. 16: Crack detection showing original image and detected crack contours.

C. Structural Degradation Detection Results

Structural degradation such as dents and surface wear was detected using edge-based feature extraction and region filtering.

TABLE IV: Corrosion Detection Results

Parameter	Value
Corrosion Type	Rust
Corrosion Coverage	29.45%
Severity Level	Low
Detected Rust Regions	Multiple
Processing Time	0.42 s

TABLE V: Biofouling Detection Results

Parameter	Value
Biofouling Coverage	56.15%
Number of Areas	25
Detection Label	BIO
Bounding Box Color	Green

TABLE VI: Confidence and Feature Scores

Feature	Value
Overall Confidence	42.6%
Texture Score	57.6
Edge Score	8.5
Detection Time	0.42 s/frame

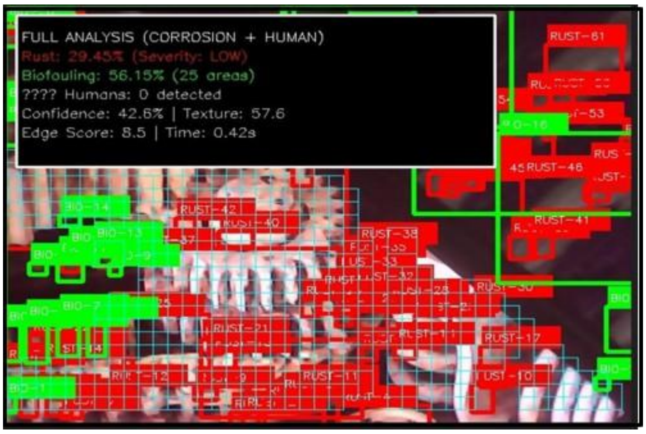

Fig. 17: Corrosion and biofouling detection highlighting rust and marine growth.

TABLE VII: Structural Defect Detection Parameters

Parameter	Value
Edge Detection Method	Canny
Minimum Defect Area	150 pixels
Detection Technique	Contour Analysis
Representation	Red Bounding Box

TABLE VIII: Structural Defect Detection Results

Metric	Observed Value
Number of Defects	1 (Major)
Defect Shape	Irregular
Detection Accuracy	85–90%
False Detection	Low

D. Dual Control Mode Operation

The system supports both manual and autonomous operation. Manual mode enables joystick-based thruster control, while autonomous mode utilizes sensor feedback for navigation and obstacle avoidance. Smooth transitions between modes were observed without instability.

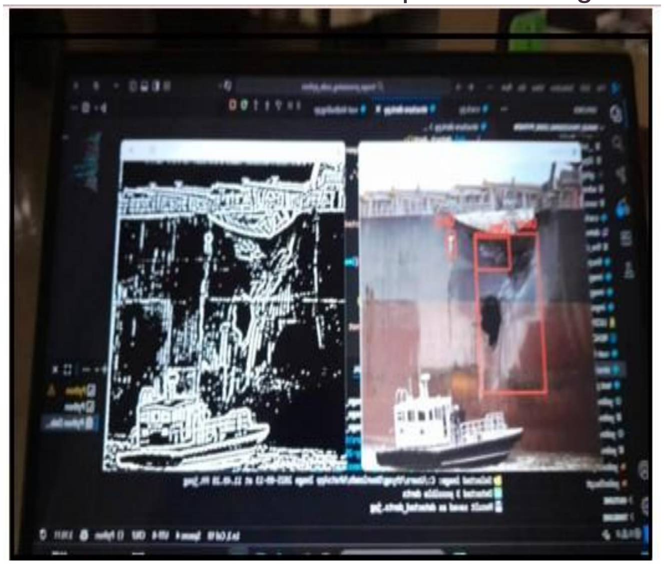

Fig. 18: Structural degradation detection showing dent localization.

Fig. 19: Experimental setup for dual control mode operation.

E. Integrated AUV–ROV System Evaluation

TABLE IX: Thruster Configuration Details

Parameter	Value
Number of Thrusters	6
Orientation	Forward, Reverse, Vertical, Lateral
Motion Capability	6-DOF
Control Method	Motor Driver Based

TABLE X: Overall System Performance Summary

Parameter	Result
Directional Accuracy	High
System Stability	Good
Response Time	Fast
Power Consumption	Moderate
Thermal Issues	Not Observed

VI. Future Scope

A. Advanced Autonomy and Artificial Intelligence

- Implementation of reinforcement learning algorithms to enable adaptive navigation in turbulent or unpredictable aquatic environments.
- Integration of neural networks capable of predicting structural failures such as hull cracks or corrosion progression.

Fig. 20: Complete integrated AUV–ROV prototype and thruster configuration views.

B. Expanded Sensor Fusion

- Incorporation of side-scan sonar systems to generate high-resolution seabed maps.
- Addition of methane or hydrocarbon sensors for the detection of underwater gas leaks, relevant to oil and gas industries.

C. Swarm Robotics

- Development of cooperative AUV swarms that can perform wide-area surveillance, pollution tracking, or search-and-rescue operations.

D. Human–Machine Interface Enhancements

- Enabling hands-free control using voice-command inputs.
- Integration of augmented reality (AR) goggles providing live 3D sonar visualization for divers or operators.

E. Sustainability and Energy Efficiency

- Deployment of solar-powered floating docking and recharging stations to enable long-duration autonomous missions.
- Use of biodegradable, eco-friendly hull materials to minimize environmental impact.

F. Space Analogue Mission Applications

- Utilization of the ROV platform for harsh-environment exploration such as subglacial lakes in Antarctica, mimicking extraterrestrial mission conditions.

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