Development of an Aquatic Wall-Clinging Robot with Photogrammetry Capability

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Abstract

Aquatic robots have wide applications in the fields of marine scientific research, underwater maintenance, and resource exploration. However, traditional aquatic robots are often limited by their motion capabilities and imaging abilities, that restricts them from conducting detailed inspection tasks. This project offers a small underwater adhesion robot that is able to continuously capture images of underwater surfaces for 3 Dimensional photogrammetric modeling. The ESP-camera module is used with a remote control handle, ROV thruster, rubber wheels, and propeller to provide stable adhesion to surfaces. Controlled experiments showed that the robot can capture overlapping images suitable for generating 3D models in underwater environments. This project's innovation is its combination of maneuverability, adaptability, and imaging capabilities in challenging underwater environments. Future improvements include autonomous navigation and better communication systems to achieve longer distances of remote control and real-time data collection.

Keywords— Photogrammetry; Negative pressure adsorption; Bernoulli's principle

Contents

1 Introduction

The Earth's surface is covered by 71% water, making underwater environments a crucial frontier for scientific exploration, industrial applications, and ecological preservation. With increasing demands for deep-sea resource extraction, environmental monitoring, and underwater maintenance, underwater robotics have become important tools in modern engineering [54]. However, these robots face challenges in performing precise inspections and capturing reliable data in turbulent water conditions. Traditional inspection methods, such as remotely operated vehicles (ROVs), often struggle to maintain stability in dynamic underwater surfaces.

Beyond industrial applications, environmental concerns emphasize the need for reliable underwater robotic solutions. In 2018, the Environmental Protection Agency (EPA) identified nearly 11,000 industrial facilities and wastewater plants illegally polluting water bodies, with factories increasingly discharging large volumes of wastewater into the sea (US GAO, 2022). Despite regulations governing wastewater discharge, tracing such discharges, often through submerged pipelines, remains challenging.

However, the challenges posed by current aquatic robots limit our ability to explore and use these underwater environments. These robots often struggle with adhesion instability, limited mobility, and complicated control systems, making them ineffective for precise inspection and maintenance tasks. To address these mobility limitations, advanced techniques in controlling the robot is applied.

Furthermore, photogrammetry offers a promising solution to challenges related to underwater inspections. It is the process of using photographs to reconstruct 3D models of objects or surfaces. It includes methods of image measurement and interpretation in order to derive the shape and location of an object from one or more photos [37]. This technique is especially valuable in underwater environments and it provides an efficient means of measurement [19]. For example, cracks or damage on ships and pipelines are difficult to detect using traditional inspection methods. Cracks can be indications of accumulated fatigue in structures, making timely monitoring essential to prevent further expansion [10]. Recording videos of ship hulls can generate continuous 2D images, which may assist in visual inspection, but motion blur, distortion, and lighting issues can reduce the reliability of quantitative measurements. Photogrammetry solves these problems by reconstructing 3D models from overlapping photographs and conducting detailed surface analysis.

This approach is useful for capturing the geometry of underwater structures in inaccessible environments. By collecting high-resolution images, a robotic system can generate a 3D model of a ship hull, so that people can conduct long-term monitoring and detection of structural problems in early periods. Incorporating photogrammetry into underwater robot, along with mobility, image capture, and computational reconstruction abilities, creates a strong tool for industrial and environmental applications.

In this paper, a small aquatic robot was designed to implement photogrammetry for underwater inspection tasks. The system was tested in controlled environments to evaluate image quality, coverage, and 3D reconstruction possibility.

2 Literature Review

2.1 Traditional Challenges

Ship hull inspection includes a crucial task in maritime maintenance, doing three purposes: safety guarantee, operational efficiency, and environmental observation (IMO, 2021). Traditional methods mainly depend on visual inspections and diver inspections, which show three limitations:

- High costs (averaging $500k) and extended rest period (5-14 days) disrupt ship schedules (Smith et al., 2019)
- Human inspectors achieve only 60-75% defect detection rates for sub-millimeter cracks in waters (Lee & Park, 2020)
- 83% of anti fouling paints release biocides exceeding EPA thresholds during manual cleaning (Marine Pollution Bulletin, 2022)

Operational efficiency is significantly affected by the hull condition since a clean and smooth hull surface reduces drag force, improving the hull's efficiency and reducing costs. Specifically, hull fouling can significantly increase fuel consumption by increasing drag, so regular inspections help maintain its performance and ensure that the hull is not affected by such obstacles. Preventive maintenance through routine inspections can save costs and reduce downtime by identifying potential problems early and making repairs and maintenance before they escalate into significant issues.

Environmental protection is another key aspect, as hull fouling can introduce invasive species to new environments and contribute to marine pollution. Regular cleaning and inspections help mitigate these risks and ensure compliance with environmental standards and regulations to protect marine ecosystems. Insurance policies often require maintaining the hull in good condition so the ship will be less likely to get into accidents or environmental damage. In addition, regular inspections and maintenance can expand a vessel's life by preventing early damage on the surface.

Ship hull inspections are important but pose significant challenges due to underwater conditions such as poor visibility, strong water currents, and marine growth like barnacles and algae. Traditional hull inspection methods often include dry inspections on the land, which are costly and time-consuming. Manual inspections are also prone to human error and may not cover the entire hull comprehensively, especially given the complex geometries and structures of ships. Furthermore, ship hull inspection can interrupt the marine ecosystem and release bad particles into the ocean, so it is essential to have new inspection guidelines.

2.2 Technological Evolution

Advancements in robotic inspection and cleaning technologies offer solutions to these challenges. Remotely Operated Vehicles (ROVs) equipped with high-resolution cameras and sensors allow for detailed and comprehensive inspections, even in low visibility conditions. Companies such as Oceaneering International, Fugro, Saab Seaeye, Deep Trekker, VideoRay, Blueye Robotics, Subsea 7, DOF Subsea, C-Tecnics, ECA Group, HullWiper, and Mariscope Meerestechnik are at the forefront of developing and deploying ROVs for ship hull inspections. First deployed in offshore oilfields during the 1980s, modern ROVs integrate multi-spectral imaging and laser scanning capabilities. While providing real-time data transmission (2-4K resolution at 30fps), their tethered operation limits maneuverability in confined spaces (Wang et al., 2021). Recent advancements in miniaturization (e.g., Blueye Pioneer at 15kg payload) both improve portability and sensor accuracy (Zhang & Ishii, 2023).

AUVs demonstrate 92% path completion accuracy in open-water procedures (Karras et al., 2022). The HUGIN Superior achieves 0.1m positioning precision through SLAM algorithms, yet struggles with dynamic current compensation (Thieme et al., 2023). Energy constraints continue, with maximum operational durations of 24-36 hours for high-power inspection models.

Magnetic adhesion systems (e.g., Jotun HullSkater) attain 200N/cm^2 adhesion force but face power consumption challenges (15W/cm^2). Vacuum-based alternatives reduce energy usage by 40% yet demonstrate vulnerability to surface irregularities (Chen et al., 2022). Recent biomimetic designs incorporating gecko-inspired dry adhesives show promise in laboratory tests (98% attachment success on corroded steel), though lack field validation (Dai & Sitti, 2023).

Modern systems use multi-modal sensing structures adding:

- Phased-array ultrasonics (PAUT) for 3D mapping (0.1mm resolution)
- Laser-induced breakdown spectroscopy (LIBS) for coating analysis
- Synthetic aperture sonar (SAS) achieving 1cm^2 defect detection at 50m range

Deep learning frameworks (e.g., ResNet-50 variants) reach 96.7% F1-score in automated defect classification, though require 10^5 annotated training samples (Nguyen et al., 2023). Edge computing implementations reduce data latency to ¡200ms but constrain model complexity (Zhao & Gupta, 2023).

The BugWright2 EU project demonstrates multi-robot collaboration, showing 30% reduction in biofouling through cooperative cleaning-inspection cycles. Compliance with IMO's 2023 Guidelines for Biofouling Management necessitates novel biofilm detection techniques using hyperspectral imaging (450-950nm bands), achieving 89% accuracy in invasive species identification (Marine Technology Society Journal, 2023).

Table 1: Comparative Analysis of Inspection Modalities

Metric	**ROVs**	**AUVs**	**Hull Crawlers**
Operational Depth	6000m	3000m	Surface
Data Bandwidth	10Gbps	2Mbps	100Mbps
Defect Sizing Accuracy	±0.5mm	±2mm	±0.2mm
Deployment Time	4-6hrs	1hr	2hrs
Environmental Impact	Medium	Low	High

Current research gaps continue in three parts: 1) energy-efficient adhesion mechanisms for rough hull surfaces, 2) full SLAM in turbid environments, and 3) standardized validation protocols for independent inspection systems.

Recent developments suggest:

- Hybrid ROV-AUV systems with adaptive autonomy switching
- Swarm robotics employing ¿10 micro-AUVs for parallelized inspection
- Digital twin integration enabling predictive maintenance through IoT sensor networks

Field trials of the Neptune Cortex system indicate 40% faster inspection cycles through edge-AI processing with 15% false-positive rates in weld inspection (OCEANS 2023 Proceedings).

In conclusion, there is a trend towards using robots and automated technologies in ship hull inspection driven by the need to improve safety, operational efficiency, and environmental protection. The advancements in ROVs, AUVs, and hull crawler robots are changing the conventional approach to ship hull inspection by offering better solutions. However, despite these developments, several gaps remain. Current systems often face challenges such as limited adaptability to complex hull shapes, difficulties in operating under strong currents or turbulent water conditions, and the need for manual intervention in data interpretation. These limitations emphasize the need for further research into autonomous and robust inspection systems.

3 Problem Statement

The primary challenge for current aquatic robots is their limited ability to operate effectively in moving underwater environments. Traditional aquatic robots often face several issues, including adhesion instability, where current robots struggle to maintain stable adhesion to underwater surfaces due to varying material properties and roughness conditions, leading to detachment and loss of functionality. The mobility of existing robots is often restricted by their design, making it difficult for them to navigate complex underwater environments, such as around obstacles or on curved surfaces. In addition, maintaining hover stability in dynamic wave flow environments requires complex control systems, which can be challenging to design and implement. Many existing aquatic robots are equipped only with basic video capture or low-resolution cameras. They lack the ability to capture overlapping images that can be processed into accurate 3D reconstructions. To address these challenges, there is a need for a more flexible and adaptable aquatic robot that can effectively capture images while moving along any underwater surface and can be controlled remotely when necessary. This robot should be capable of operating in a wide range of underwater environments and be scalable for various applications.

4 Overall design

The objective of this project is to design a flexible aquatic mobile robot to address challenges in capturing images underwater. In the design, the following requirements need to be taken into consideration:

1. The robot should be able to move on the wall of underwater pipelines, spanning an angle range of 60 to 300 degrees from the vertical, which requires it to have adsorption and movement mechanisms that can adapt to different angles. By controlling the outer propellers, the robot can achieve angular rotation.

2. The robot should be able to cling on the wall surface.
3. The robot is equipped with thrusters to achieve propulsion in water, as well propellers to move and turn on walls. These motors are controlled by a remote control handle.
4. The robot incorporates a camera module for photogrammetry. The camera is programmed to capture images during motion.

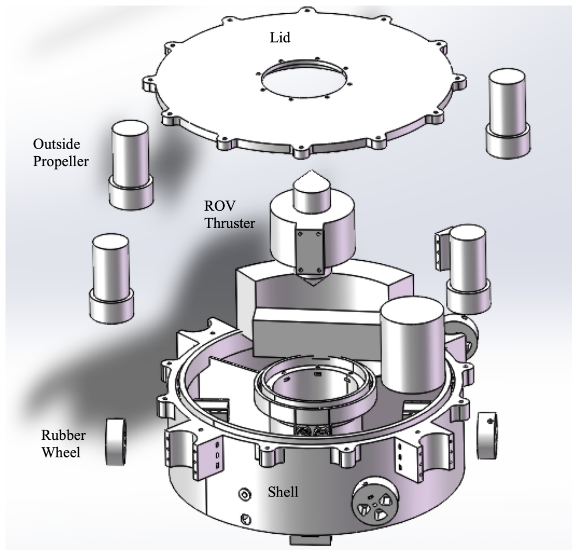

Figure 1: Robot with parts labeled.

5 Theoretical design of adhesion mechanism

Designing a robot to stably cling on the wall and achieve omnidirectional movement requires a mobile platform and an adsorption module to ensure tight adhesion to the wall.

Considering the need to achieve the function of moving on the wall while clinging, suction cups and adhesive materials have been ruled out, given that the use of adhesive materials may lose effectiveness underwater due to factors such as water intrusion, material degradation, or weak adhesion. Furthermore, the adhesive application and removal procedures may be relatively cumbersome, increasing operational complexity. Magnetic adhesion may not apply to all underwater surfaces and requires special surfaces or materials with magnetic properties. Meanwhile, maintaining reliable magnetic connections is challenging under different underwater conditions and therefore may not be feasible in some cases. Therefore, the negative pressure mode is adopted.

5.0.1 Bernoulli's principle

The ROV thruster accelerates the fluid beneath the robot, resulting in a pressure drop compared to the outside pressure, described here as "negative pressure" (although it is really just the difference that is negative).

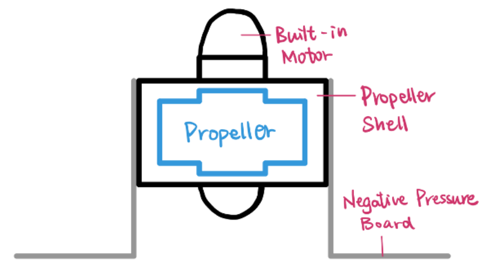

Figure 2: Cross-section diagram of underwater Bernoulli's suction cup structure

In the water close to the wall, assuming that the propeller of the thruster rotates counterclockwise, the direction of the water flow is from bottom to top. As shown in the figure below, there will be a certain gap between the negative pressure effect plate and the wall due to the rubber wheel. When the propeller rotates in the forward direction, it will suck in the fluid around the gap and discharge it from the top of the suction cup through the guide vanes, during which a high-speed fluid will form within the gap, resulting in the Bernoulli's effect, causing the pressure at that location to be lower than the environmental pressure in free water.

The adsorption force comes primarily from this negative pressure below the robot, with some additional force coming from momentum transfer by the ROV thruster propeller.

6 Program design

The robot utilizes a program written in Arduino, combined with the ESP32 module connected to the remote, to control HC-12, PS2-a, PS2-b, and buttons. By connecting the HC-12 module with Mega2560, remote control of the ROV thrusters, rubber wheels, and propellers are achieved.

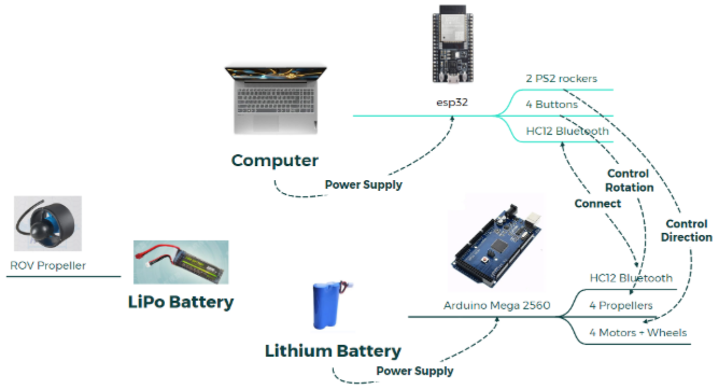

Figure 3: Robot scheme design.

This project consists of two main components: a self-made remote control and a robot program. The former is used for remote operation and control of robots, equipped with two PS2 joysticks, which are respectively used to control the speed of the ROV thruster and the direction of the rubber wheels. In addition, the four buttons on the remote are used to control the rotation of the robot's propeller. The program detects which button has been pressed and sends the corresponding signal to the HC-12 Bluetooth module on the robot.

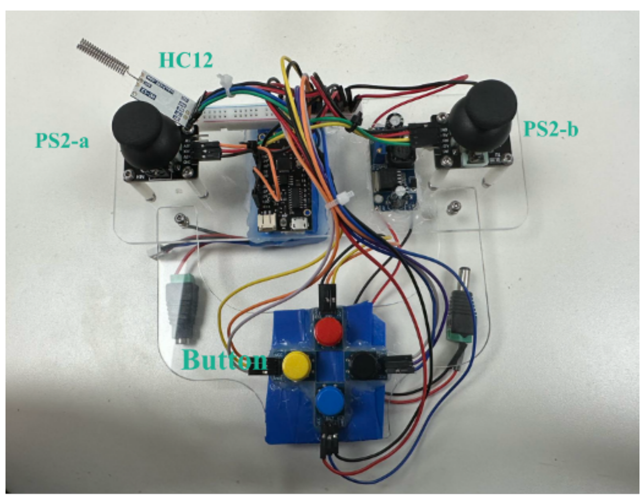

Figure 4: Position annotation of remote control parts in the first version.

In terms of robot programs, it is necessary to receive instructions from the remote control and execute corresponding tasks. Firstly, the HC-12 Bluetooth module is used to receive commands sent by the self-made controller. According to instructions, the program controls the start, stop, and speed of the ROV thruster to ensure that the robot can move forward, backward, and hover in the water; And the direction and speed of the rubber wheels enable the robot to move on the wall of the underwater pipeline. According to the signal of the button, the program controls the rotation direction of the robot's propeller.

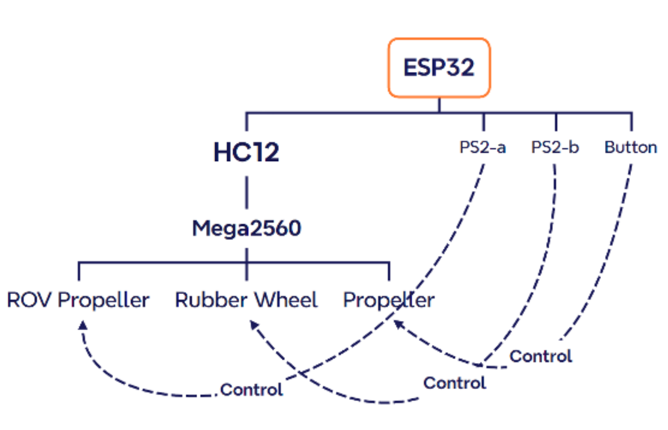

Figure 5: Program design diagram.

7 Photogrammetry Methods and Image Testing

7.1 Introduction to Photogrammetry

Photogrammetry is the process of using photographs to reconstruct 3D models of objects or surfaces. It includes methods of image measurement and interpretation in order to derive the shape and location of an object from one or more photos [37]. This technique is especially valuable in underwater environments and it provides an efficient means of measurement [19].

Underwater cracks or damage on ships and pipelines are difficult to detect using traditional inspection methods. Cracks can be indications of accumulated fatigue in structures, making timely monitoring essential to prevent further expansion [10]. Recording videos of ship hulls can generate continuous 2D images, which may assist in visual inspection, but motion blur, distortion, and lighting issues can reduce the reliability of quantitative measurements. Photogrammetry solves these problems by reconstructing 3D models from overlapping photographs and conducting detailed surface analysis.

7.2 System Setup

The robotic system was designed with the following components:

- Camera (high-resolution color, chosen for improved visibility in underwater conditions)
- Flashlight for illumination in low-light environments

- Humidity sensor and buzzer for leak detection
- SD card for image storage

Waterproofing was achieved by sealing the camera in a transparent housing and enclosing other electronic components with rubber seals. To stabilize the robot in the presence of water movement, propellers were used. The robot was programmed to move in straight lines across surfaces to ensure systematic coverage of the target object. Images were processed using Agisoft Metashape using default alignment and sparse point cloud settings.

7.3 Experimental Methods

The camera was used to capture one image every two seconds, with all photos stored on an SD card. To address the challenge of low-light environments, a built-in flashlight was used to provide illumination and improve image clarity.

In addition, a humidity sensor and buzzer were integrated into the system. The humidity sensor was designed to detect water leakage inside the robot, while the buzzer provided an immediate alert to people.

Testing was first conducted in a bathtub environment by photographing an object from multiple angles. However, reflections from the object and bathtub surfaces interfered with photogrammetric reconstruction. To address this, non-reflective objects were later used, which significantly improved results.

8 Results

Through successive iterations, several important understandings were gained:

- **Object pattern and surface texture:** Only the keyboard images achieved image alignment in Metashape. Both the bathtub and kettlebell images failed to generate models due to visual reflections and surfaces with no distinct features.
- **Camera resolution:** The ESP32-CAM produced smoothened images with low contrast. Hence, this weakened Metashape's ability to identify keypoints between pictures.
- **Lighting conditions:** Indoor lighting reduced image details, reducing the variability needed for photogrammetry.
- **Motion control:** Without stabilized or motor-controlled movement, image overlap was inconsistent.

While full 3D reconstruction was not achieved, these experiments produced valuable constraints and learning outcomes. The successful alignment on the keyboard object indicates that the robot camera setup has potential, but is limited by environmental conditions, camera optics, and control.

The bathtub tests demonstrated challenges because of its reflective surfaces that reduced the reliability of photogrammetric reconstruction. To address this problem, different objects were used in later trials. A kettlebell was chosen as another 3D object, but its dark and smooth surface lacked variation for accurate modeling. In addition, the low-cost camera produced smoothed images that has lower sharpness.

A breakthrough occurred when selecting a computer keyboard as the imaging object. Its repeated kay patterns provide clear and consistent features in continuous images, greatly improving image matching. The camera was moved slowly across the keyboard surface that mimicked the robot's inspection process. In this way, image sets were produced that were more suitable for 3D reconstruction.

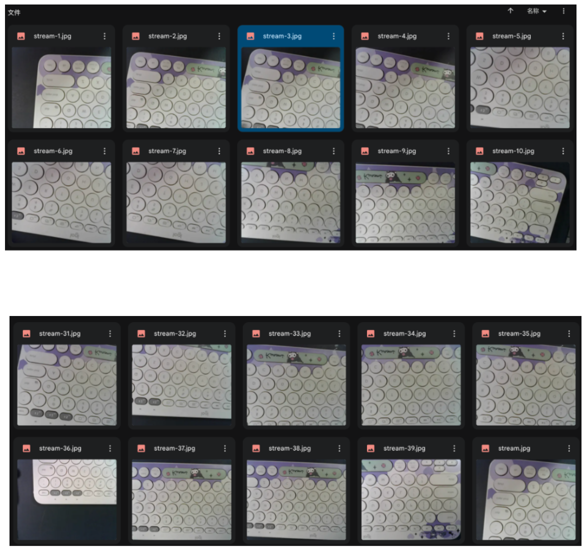

Figure 6: Keyboard photos

Sample output showed that photogrammetric modeling was feasible, though lighting reflections and object surface properties remained challenges.

9 Discussion

Although the setup did not automatically identify cracks or corrosion, photogrammetry provided accurate 3D surface reconstructions for human inspection.

The simulations produced important lessons about the requirements for successful image-based reconstruction. First, surfaces must provide distinguishable visual features for the software to detect and match them. Flat objects, such as the bathtub, failed because they lacked patterns. On the other hand, objects like a keyboard allowed the software to align easily.

Lighting was also very critical for modeling. Lighting created reflections and reduced surface detail, which confused the software and produced image noise. Natural or carefully placed artificial light is more effective in reducing reflections and improving the visibility of surface features. Since natural light in environments tends to be more diffuse, some of the difficulties observed during simulations may not be as severe in real underwater applications. Glossy surfaces, such as kettlebells, exhibit unpredictable image features that can vary between photos, making feature matching unreliable. Therefore, surfaces with a matte finish or low reflectivity are more suitable for photogrammetry.

The quality of the camera was another limiting factor. The relatively low resolution and smoothing artifacts of ESP32-CAM decreased the visibility of details, even when photos overlapped well. This weakens keypoint detection and ultimately limits the accuracy of reconstruction. Higher resolution and clearer cameras are crucial for more reliable results.

In addition, the number and overlap of photos proved to be critical. A larger collection of overlapping images captured from multiple angles increases the likelihood that the software can triangulate spatial positions and assemble a 3D model. In principle, a programmed capture rate of one image every two seconds is effective, but the lack of stability or motor control motion can lead to uneven overlapping.

Finally, camera noise in low-light environments also causes problems. ESP32-CAM compensates for poor lighting by increasing noise and blur in the image. By improving lighting strategies or using higher quality cameras to reduce noise, the processing results will be greatly improved.

Collectively, these lessons form a practical index for future low-cost photogrammetry experiments. Although complete 3D reconstruction has not yet been achieved, these technical points lay the foundation for designing more effective imaging protocols under simulated and underwater conditions.

Summary and outlook

In this paper, the design and implementation of an aquatic robot with flexible mobility is introduced, which is capable of clinging to the outside and walls of underwater pipelines and ship hulls to perform tasks. In order to achieve this goal, the robot adopts a negative pressure adsorption mechanism, combined with the control of ROV thrusters, rubber wheels, and propellers, to achieve omnidirectional movement and directional operation. In addition, it is equipped with various sensors and tools to meet the needs of different tasks. In terms of hardware design, the robot adopts key components such as the Arduino Mega2560 control board and HC12 Bluetooth module. Through precise control of the power system, it achieves power supply to various parts of the robot. The shape of the robot is designed with a cylindrical structure to reduce the resistance and buoyancy in the underwater environment and improve the stability.

This project also demonstrated that photogrammetry can be implemented on a small underwater robot to capture detailed images of submerged surfaces. While reflections and lighting presented challenges, the approach successfully generated photo sets suitable for 3D reconstruction. Future work will focus on improving waterproofing, enhancing image quality with diffused lighting, and incorporating automated crack detection algorithms.

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