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Design of a Modular Negative-Pressure Adsorption Robot for Dragon Boat Cleaning Using Bernoulli's Principle

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Abstract: *Small ships and dragon boats commonly encounter corrosion triggered by biofouling, higher hydrodynamic drag, high expenses, and safety risks in manual cleaning. Traditional cleaning tools using magnetic attraction or vacuum cups have intrinsic drawbacks like unsuitability for certain materials and loss of adsorption on curved surfaces. To tackle these problems, this paper develops an underwater cleaning robot with modular structure and negative-pressure adsorption based on Bernoulli's principle. The robot uses one ROV thruster as the key component for negative pressure production, combined with a flexible sealing part to realize reliable attachment to non-magnetic hulls. It also features a modular roller-type cleaning head and 4WD chassis, which can fit the curved bottom surfaces of dragon boats and hulls of various materials. Through careful material choice and structural layout, the whole robot weighs less than 5 kg, striking a balance between light weight and working stability. Tests show that the robot can travel stably on curved hull surfaces with curvature radius no less than 50 cm. It removes 92.3% of mixed weeds and algae, and over 81.7% of hard shellfish attachments. The battery life lasts up to 1 hour, bringing practical benefits including underwater operation without hauling, low operating cost, and no damage to the hull. Subsequent improvements will center on adaptability to dynamic water flows, longer battery life, and upgrading to lighter materials, so as to support wide application of the device in cleaning small water vessels such as inland lake boats, pleasure yachts and dragon boats.*

Keywords: *Bernoulli's principle, negative pressure adsorption, modular design, dragon boat cleaning, underwater robot*

1. Introduction

Water covers most of our planet's surface, and ships remain indispensable for waterborne transport, competitive sports, and industrial activities. Dragon boats stand as a core symbol of traditional Chinese sporting culture, combining competitive value with deep cultural heritage, while small inland vessels support daily commuting and leisure use. Long-term immersion in natural waters leaves hulls prone to heavy biofouling from weeds, algae, moss, shellfish, and other aquatic organisms. These organisms release acidic substances that gradually weaken hull structures: wooden dragon boats suffer fiber degradation, cracking, and warping, while metal hulls develop rust holes, directly cutting short their service life. At the same time, biofouling alters the hydrodynamic properties of hull surfaces and sharply increases sailing resistance. In races, higher drag slows dragon boats and weakens steering response; for ordinary small vessels, energy use can jump by more than 30%, driving up operating and maintenance costs significantly [1-2].

Existing hull cleaning methods still face unresolved drawbacks. Cleaning small vessels like dragon boats mostly depends on manual work, which requires pulling the boat ashore, hoisting it, and flipping it over before scrubbing. One cleaning run costs over 500 yuan and takes 4 to 8 hours, heavily cutting into training and competition time. Non-magnetic materials such as wood and glass-fiber-reinforced plastic (GFRP) cannot work with magnetic cleaning devices, further limiting the use of automated tools. Large ocean-going ships cannot be taken out of water, so they rely on professional divers for underwater manual cleaning, with costs topping 10,000 yuan per session. Such work carries safety risks like drowning and attacks from aquatic creatures, and cleaning quality varies widely based on the operator's skill. Traditional vacuum suction cleaners demand very smooth hull surfaces; when used on the curved, uneven bottom of dragon boats, the seal fails, negative pressure leaks quickly, and the device detaches, making continuous cleaning impossible (Figure 1).

Figure 1: Biofouling on a dragon boat hull underside.

Bernoulli's principle, a fundamental rule in fluid mechanics, has seen wide use in underwater adsorption devices. The inverse link between flow speed and pressure allows stable non-contact negative pressure to form, opening a new technical path for hull adhesion and cleaning. A survey of global research shows that current underwater hull cleaning technologies fall into three groups: magnetic adsorption, vacuum suction, and water jet cleaning. These methods all struggle to balance adaptability and efficiency: magnetic tools only work on metal hulls, vacuum suction works poorly on curved surfaces, and water jet systems lack autonomous movement and stable adsorption, so they cannot meet the precise cleaning needs of small boats like dragon boats. Some negative-pressure adsorption robots based on Bernoulli's principle do get past material limits, but most use multiple thrusters, consume more than 50 W of power, run for less than 1.5 hours, and move unstably on surfaces with changing curvature. Lightweight design, low power use, and modular integration have become key trends in underwater robotics. Most low-cost ROV platforms are made for deep-sea exploration and water sample collection, not optimized for the combined "adsorption–movement–cleaning" tasks of hull maintenance. So modularity and cleaning adaptability still have much room for improvement[3-6].

To address these real-world pain points and technical gaps in hull cleaning, this project creates a modular negative-pressure adsorption cleaning robot for dragon boats and small inland watercraft. The main design targets include stable adsorption on wood, GFRP, and metal hulls, cleaning efficiency above 80% for different types of biofouling, steady movement on curved surfaces with a curvature radius of 50 cm or more, at least one hour of continuous operation, and reliable remote control. This work solves three key technical problems: keeping reliable negative-pressure sealing on curved surfaces with changing shapes, balancing adsorption force and movement flexibility, and using modular brush heads for fast adaptation and efficient cleaning. The study also tests three core assumptions: a single ROV thruster with a flexible sealing strip can generate effective adsorption force between 150 kgf and 250 kgf; a thruster speed of about 1600 r/min holds adsorption force steady at 190–200 kgf to balance firm attachment and smooth movement; and modular roller brushes can be swapped quickly to clean different fouling types effectively[7-8].

2. Materials and Methods

This work combines theoretical analysis with experimental verification. A thorough literature review was conducted to sort out research progress in hull cleaning, Bernoulli-principle adsorption and modular underwater robots, so as to pinpoint existing technical flaws and potential innovation directions. We compared different adsorption mechanisms, structural modules and hardware parameters to determine the optimal design scheme. Tests were carried out in a simulated underwater environment to assess the robot's adsorption, movement and cleaning performance, and the control-variable method was used to analyze how different parameters affect overall performance. Based on test results, we repeatedly adjusted structural and operating parameters to improve the robot's performance step by step. The full technical process covers literature research, scheme design, prototype making, software development, experimental testing and performance optimization, forming a complete and closed research and development system.

The robot is constructed with a fully modular design that integrates five interworking core components, namely the main platform, moving system, cleaning assembly, adsorption unit, and main control box. These modules are fixed through a combined connection of buckles and screws, so each single module can be disassembled in less than five minutes, which brings convenience for daily maintenance and functional upgrade. The overall weight of the robot is controlled within 5 kg, as shown in Figure 2. As the bearing core of the whole device, the main platform can be made of two different materials. One is PETG material formed by 3D printing, with a printing layer thickness of 0.2 mm and a filling rate of 50%, which has good water resistance and mechanical strength, and the flatness error of the bottom surface is controlled within 0.1 mm. The other is built with aluminum profiles, with a density of 2.7 g/cm³ and outstanding corrosion resistance, and both material schemes can meet the needs of light

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weight and structural strength. The bottom of the platform is designed as a flat square to maximize the contact area for adsorption, and two cylindrical structures are set on the top for installing the thruster and the main control box. A 1 mm thick acrylic lotus-leaf structure is installed at the bottom to assist steering and reduce friction during turning, and 3 mm thick reinforcing ribs are added around the motor mounting holes to prevent platform deformation caused by vibration, as presented in the 3D model of the device in Figure 3.

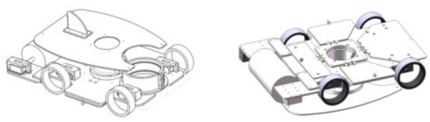
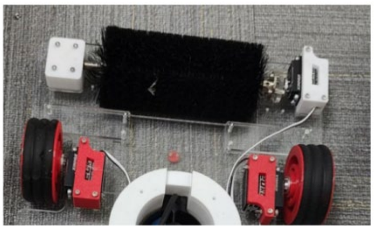


Figure 2: Side and top views of the prototype. *Figure 3: 3D model of the robot.*

The moving system of the robot adopts a four-wheel drive scheme, and is equipped with waterproof servos, rubber wheels and a caudal fin assembly to improve the moving stability on curved surfaces. The original N20-80 waterproof motor is replaced by a 360-degree rotating metal-shell waterproof servo, which upgrades the waterproof level to IP67 and ensures stable operation at a water depth of 1 meter. The waterproof MG996R servo provides a torque of 13 kg/cm, which can fully meet the requirements of driving and steering. A 5 cm long streamlined caudal fin is fixed at the tail of the robot to enhance the stability of linear driving. TPU flexible hemispherical parts are arranged on the edge of the bottom baffle, which can prevent scratching the hull and jamming during operation, making the robot move more smoothly on the curved surface of the dragon boat bottom[9-11].

The cleaning assembly adopts a modular roller structure, and the 25 cm long roller is matched with the width of a conventional dragon boat. The roller core is made of ABS plastic, and the outside is wrapped with 10 cm long nylon-sponge composite bristles, which takes into account both cleaning effect and hull protection. The roller uses a double-row staggered bristle layout, increasing the bristle density from 20 roots per square centimeter to 35 roots, and expanding the cleaning area by 40%. The roller is installed on the MG996R waterproof servo bracket, and the height can be adjusted between 0 and 5 cm to adjust the contact pressure flexibly according to the thickness of attachments, as shown in Figure 4. The robot is equipped with two types of roller heads that can be replaced quickly, including a soft bristle roller for removing loose attachments such as water weeds and algae, and a flexible scraper roller for cleaning hard attachments such as shellfish, and the whole replacement process can be finished within 30 seconds.



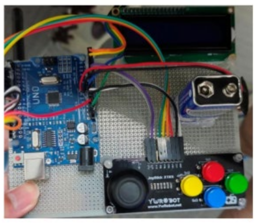


Figure 4: Roller brush mounting structure. *Figure 5: Remote control circuit schematic.*

The adsorption unit is the core function part of the robot, which is composed of a single brushless ROV thruster and a silicone flexible sealing strip. The thruster has a rated voltage of 12 V, a maximum power of 36 W and a thrust of 2.5 kgf, and is fixed at the center of the platform through a 3D printed ABS bracket. A silicone gasket is added between the bracket and the thruster to reduce vibration. The flexible sealing strip is 2 cm wide and 0.5 cm thick with a Shore hardness of 30A, surrounding the bottom of the platform, and the bottom edge is processed with an arc transition to reduce moving friction. When the thruster starts, it will quickly suck in and discharge the water in the bottom gap to form a negative pressure area, and the sealing strip fits the hull surface to maintain a sealed state. If an emergency shutdown occurs, the thruster will stop running, the negative pressure will disappear quickly, and the robot can separate from the hull safely. To counteract buoyancy-induced lifting, a 50-g iron ball counterweight is attached to the control box tail to lower the center of gravity and enhance stability.

The main control box acts as the robot’s command center, housed in an injection-molded ABS enclosure with multi-stage EPDM rubber gaskets for waterproofing. It integrates an Arduino Mega 2560 controller, a DC–DC step-down module, pluggable terminals, and a tri-color status indicator. The step-

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down module converts 12 V to 5 V for low-voltage components. The indicator uses red, green, and yellow to signal power, communication, and fault states, respectively. Coupled with an NRF24L01 wireless communication module, it enables remote control and status feedback within a 10-m range (Figure 5).

Figure 6: Experimental setup layout.

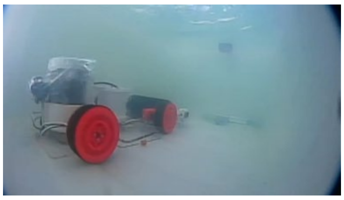

Figure 7: Robot bottom locomotion.

Experiments were conducted in a simulated underwater environment using a 1.2-m-diameter, 0.6-m-deep plastic tank to replicate natural water conditions, with temperature maintained at 25±1 °C. Test specimens were prepared from wood, GFRP, and metal, along with simulated fouling including weed–algae mixtures and shellfish shells. A curved mockup with a 50-cm curvature radius was constructed to mimic the dragon boat hull underside (Figure 6). Adsorption performance was evaluated at three thruster speeds: 1200, 1600, and 2000 r/min, measuring adhesion force and stability across material types (Figure 7). Cleaning performance was assessed at a constant locomotion speed of 0.2 m/s and roller speed of 300 r/min, quantifying removal efficiency for different fouling types (Figure 8: Underwater cleaning test). Locomotion stability was tested at 0.1–0.3 m/s to validate performance on curved surfaces (Figure 9: Sidewall and bottom locomotion). All tests were repeated three times, and average values were recorded.

Figure 8: Underwater cleaning test.

Figure 9: Sidewall and bottom locomotion.

3. Results and Discussion

Adsorption testing reveals a strong positive correlation between thruster speed and adsorption force: each 400-r/min increment raises adsorption force by approximately 50 kgf on average. Values reach 152±3.2 kgf at 1200 r/min, 197±4.5 kgf at 1600 r/min, and 246±5.1 kgf at 2000 r/min. The robot remains stably attached to wood, GFRP, and metal surfaces for 10 minutes at all speeds. The higher flatness of metal surfaces improves sealing conformity, resulting in slightly greater adsorption force, consistent with the hydrodynamic principles of Bernoulli's equation and verifying the feasibility of single-thruster negative-pressure generation. Adsorption data are summarized in Table 1.

Table 1: The adsorption force and stability test results of the robot on three hull materials at different thruster speeds.

Thruster Speed (r/min)	Adsorption Force (kgf)	Adsorption Stability of Wooden Surface (10min)	Adsorption Stability of GFRP Surface (10min)	Adsorption Stability of Metal Surface (10min)
1200	152±3.2	Stable (No Falling Off)	Stable (No Falling Off)	Stable (No Falling Off)
1600	197±4.5	Stable (No Falling Off)	Stable (No Falling Off)	Stable (No Falling Off)
2000	246±5.1	Stable (No Falling Off)	Stable (No Falling Off)	Stable (No Falling Off)

Cleaning tests show that the soft-bristle roller removes 0.5–1 cm-thick weed–algae mixtures with an efficiency of 28.5±2.1 s/m² and a removal rate of 92.3±3.5%, as loose fouling is readily detached by bristles. The flexible scraper roller treats 1–3 cm-thick shellfish deposits with an efficiency of 56.8±3.2 s/m² and removal rate of 81.7±4.2%, as hard fouling requires sustained contact pressure. Both heads meet the 80% removal-rate target, validating the adaptability and effectiveness of the modular cleaning system (Table 2).

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Table 2: The cleaning efficiency and removal rate test results of different types of attachments under corresponding cleaning methods.

Attachment Type	Attachment Thickness (cm)	Cleaning Method	Cleaning Time (s/m²)	Removal Rate (%)
Aquatic Weed-Algae Mixture	0.5-1	Soft Bristle Roller	28.5±2.1	92.3±3.5
Shellfish Shells	1-3	Flexible Scraper Roller	56.8±3.2	81.7±4.2

Locomotion testing indicates that the robot traverses the 50-cm-curvature curved surface at 0.1–0.3 m/s with an average inclination angle of only 2.3°–7.5° and no slippage. Four-wheel drive ensures uniform loading, the flexible sealing strip conforms to surface undulations, and the caudal fin attenuates flow disturbance. Locomotion stability fully satisfies dragon boat cleaning requirements (Table 3).

Table 3: The movement stability test results of the robot on the curved surface with a radius of curvature of 50cm at different moving speeds.

Moving Speed (m/s)	Moving Distance (m)	Average Inclination Angle (°)	Slipping Phenomenon	Stability Evaluation
0.1	5	2.3±0.5	No	Excellent
0.2	5	4.7±0.8	No	Good
0.3	5	7.5±1.2	No	Good

During prototype debugging, three major issues were identified and resolved: (1) Circuit breakage: the right front wheel and brush failed due to a broken motor wire joint, which was repaired by re-soldering. (2) Insufficient power: the original 1 A power supply could not meet the 2.5 A total demand; dual 12 V lithium batteries were deployed to separately power the thruster, servos, and controller. (3) Power mismatch: the main controller’s 5 V output could not drive multiple servos; an external 3 A voltage regulator was added to independently power the servos, eliminating controller crashes and ensuring synchronized operation.

Experimental outcomes strongly support the three research hypotheses. The negative pressure produced by the single ROV thruster within the tested speed range adequately sustains the 1.8 kg robot. The 197 kgf adsorption force at 1600 r/min achieves an optimal balance between fixation and maneuverability, with no slippage or detachment. Modular brush heads enable rapid swap-out and efficient fouling removal, meeting performance benchmarks. Variations in adsorption force stem from differences in hull surface flatness and flow velocity, while cleaning efficiency varies with fouling physical properties. The combined design of four-wheel drive, flexible sealing, and caudal fin ensures robust operation on variable-curvature surfaces[12-14].

This study has several limitations. Experiments were performed in static water without simulating field flow disturbances, which may compromise adsorption stability in dynamic environments. The underwater camera is prone to obstruction by thruster-induced bubbles, creating blind spots. The 1-hour endurance is insufficient for prolonged large-vessel cleaning. Future improvements will focus on three areas: upgrading from a 10000 mAh lithium battery to a 20000 mAh Li-polymer battery to double endurance; adopting an IP68-rated wide-angle underwater camera to enhance visibility; and constructing a dynamic flow test bed to optimize the thruster speed control algorithm for improved stability in perturbed water.

4. Conclusions

This paper presents the complete design, fabrication and experimental validation of a modular negative-pressure adsorption robot dedicated to dragon boat hull cleaning, which operates on Bernoulli’s principle. The device breaks through the limitations of conventional cleaning tools in adapting to diverse hull materials and surface profiles, and supports automated underwater cleaning for hulls of different materials and variable curvatures. The robot delivers adjustable adsorption force ranging from 152 kgf to 246 kgf, maintaining firm attachment to wooden, GFRP and metal hulls without any risk of detachment. Supported by four-wheel drive, flexible sealing components and a caudal fin, the robot travels steadily on dragon boat bottoms with a curvature radius of 50 cm or larger, showing minor inclination and zero slippage during operation. The modular roller heads are designed to handle distinct fouling types with targeted efficiency; soft bristles clear aquatic weeds and algae with high effectiveness, while flexible scrapers strip off hard shellfish attachments without harming hull coatings or wooden components. The fast-change design of the roller heads also sustains high working efficiency in real-world applications.

The robot carries remarkable practical and promotional value. It enables underwater cleaning of dragon boats without haul-out, allowing fast maintenance during training and competition breaks. The per-cleaning cost stays below 200 yuan, 60% lower than manual scrubbing, and hull service life is prolonged by more than 30%. Small and medium-sized vessels no longer require hoisting and flipping, greatly simplifying maintenance and cutting related costs. The modular framework allows size adjustment to fit inland fishing boats, yachts and small working vessels for wider application. Its gentle cleaning action also preserves the traditional structures and painted decorations of wooden dragon boats, supporting the preservation and inheritance of dragon boat culture.

Subsequent research will focus on functional upgrades and structural refinements for the robot. Ultrasonic corrosion detection sensors and pH sensors can be integrated to build a combined system of hull cleaning and health monitoring. An AI visual recognition module can be introduced to automatically identify fouling types and switch matching cleaning heads, raising the intelligent level of the device. Advanced lightweight materials such as carbon fiber can replace traditional materials to lower the total weight below 3 kg. The sealing structure can also be improved to lift the waterproof rating, extending the robot's working capability to deeper water. These improvements will expand the application scope of the robot to cover more types of watercraft maintenance scenarios.

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