Review Article

Overview of Underwater Robots for Hull Cleaning

ABSTRACT

At present, the cleaning of the hull surface in China is carried out in the dock, and the cleaning equipment that can be successfully used in underwater operations still needs the assistance of divers in the water, which is high cost and low efficiency. This paper introduces the current situation of hull cleaning robots at home and abroad, as well as the advantages and disadvantages of related technologies, such as dock cleaning technology, underwater cleaning technology, etc., and analyzes the development trend of underwater hull cleaning equipment in the future, providing a theoretical basis for the development of hull cleaning equipment.Underwater cleaning robots have been a rapidly developing research and application field in recent years. Its main goal is to perform cleaning, maintenance, and monitoring tasks in an underwater environment by automated or semi-automated means. Such robots are used in a wide variety of application scenarios, including but not limited to oilfield maintenance, marine debris removal, reservoir and pond management, and ship maintenance study design: Underwater cleaning robots are capable of working long hours in harsh environments and their programmability and versatility enable them to perform a variety of complex tasks. In addition, with the development of advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), and deep learning, the level of intelligence of these robots is also gradually improving. With global industrialization and population growth, the problem of underwater environmental pollution is becoming more and more serious. Traditional underwater cleanup methods often rely on human labor, which is not only inefficient but also can pose a safety risk to workers. Therefore, automation technology has great potential and value in this field. To sum up, underwater cleaning robot is a multidisciplinary field, involving mechanical engineering, electronic engineering, computer science, and environmental science. It not only contributes to solving current pressing environmental problems but also provides new research and application opportunities in related fields.

Keywords: Underwater cleaning; Development dynamics; Analysis of current situation; Theoretical basis.

1. INTRODUCTION

When ships operate in the water, the surface of the hull is susceptible to the attachment of various organisms such as algae, shellfish, worms, etc. This biological attachment is called "biological contamination". Biological pollution not only affects the appearance of the vessel, but also leads to increased drag on the vessel, which increases fuel consumption and reduces the speed of the vessel. Traditional cleaning methods may use harmful chemicals, which are harmful to the Marine environment. Therefore, it is particularly important to find environmentally friendly and effective cleaning methods. With the rapid development of robotics, sensing technology and computer vision technology, it is possible to develop robots that can clean the hull automatically or remotely. Robots can clean the hull more quickly and accurately than manual methods. The robot can work in a variety of environmental conditions, is not limited by depth, and can work continuously without the need for rest. Hull cleaning is an important link in shipping and ship maintenance, which has multiple benefits such as reducing fuel consumption, improving speed, and protecting the marine environment. However, the traditional hull cleaning methods such as manual operation by divers are not only labor-intensive and costly but also have certain safety risks. In recent years, with the rapid development of robotics and artificial intelligence, hull-cleaning robots have gradually become the focus of this field. They can perform cleanup tasks efficiently and safely in a variety of water conditions and have tremendous economic and social value.

The purpose of this review is to introduce the research and application status of the hull cleaning robot and discuss its technical challenges and development trends. We will conduct an in-depth analysis of the robot's structural design, cleaning methods, navigation systems, and interaction with the environment, and summarize its application cases in various ship and water environments. Through this review, we hope to provide reference and inspiration for the research and development and practical application of hull cleaning robots.

2. METHODOLOGY

2.1 HIGH-PRESSURE WATER JET CLEANING TECHNOLOGY

Conventional ship cleaning is carried out when the ship is dry-docked. Therefore, in addition to removing some of the Marine fouling attached organisms from the surface, the cleaning in the dock also includes the damaged anti-fouling coating and the rusted substrate, in preparation for the subsequent painting process

At present, the main cleaning technology is high-pressure water jet cleaning. The difference between cleaning and de-rusting is their variation in the working pressures. The general cleaning pressure is 70MPa, and the de-rusting pressure is 220MPa.[1]. So, dock cleaning is mostly rust removal. Due to the high requirements of rust removal, water jet technology is developing from high pressure to ultra-high pressure and high power. However, the recoiled force of the water jet during manual gun operation (which cannot exceed 1/3 of the body's own mass) greatly limits its development. A high-pressure water jet, also called a water knife, this "water jet" speed is generally more than 1 times the Mach number, with a huge impact energy. This kind of high energy, high-speed water flow forward or tangential impact on the surface of the object has a strong effect, so as to complete the cutting, cleaning, crushing, finishing, and other operations. High-pressure water jet cleaning is an environmentally friendly and economical surface treatment method, which has been widely used in industry and Marine engineering. The high-pressure water rust remover developed by Hefei General Machinery

Research Institute using high-pressure water jet technology can achieve the effect of replacing a manual hand-held spray gun with an automatic wall-climbing robot, vacuum recycling rust residue, and ensuring robot wall attachment. As an actuator, the robot is equipped with an ultra-high pressure rotary joint and a nozzle composed of four nozzles. [2]The rotating motion of the nozzle is driven by the torque formed by the recoiling force of the nozzle jet. The plate clearance seal of the rotary joint makes the nozzle stable and reliable when rotating under ultra-high pressure.

2.2 SAND-BLASTING

Hull sandblasting cleaning refers to the use of compressed air to drive abrasives to the surface of the workpiece at a certain speed, through the abrasive impact of the hull surface of the oxide, rust, and Marine dirt to remove, this process is a more mature way of hull cleaning industry, up to now many shipyards are still in use [3]. However, because the technology is cleaned by pneumatic abrasive, the noise is large, the pollution of the environment is more serious, and manual participation is required, so the human body will suffer from occupational diseases such as "silicosis". High-pressure water cleaning and sandblasting in the dock need to clean the hull surface after the ship enters the dock, which has the problems of long repair time and insufficient dock and also increases the non-operating time of the ship and fuel consumption. In addition, sandblasting will bring serious pollution to the working environment.

2.3 UNDERWATER CLEANING ROBOT TECHNOLOGY

The quantity of large docks in China is insufficient; the docking time is long, the cost is expensive, and it is easy to cause the loss of stoppage and increase the transportation cost. In addition, during a docking cycle, the greenhouse gas emissions caused by the degradation of ship navigation performance account for 9% to 12% of global fleet greenhouse gas emissions, so flexible and convenient underwater cleaning technology is necessary [4]. At present, underwater cleaning and maintenance technology has been recognized by classification societies and other parties, allowing underwater inspection instead of intermediate inspection, and extending the docking interval for up to 12 years. Especially at present, the recovery of the shipping market is weak, the shipping capacity is idle, the speed of ships is reduced, and the pollution problem will be more prominent [5]. Regular underwater cleaning combined with specific anti-fouling paint can reduce the damage of idle and slow sailing ships, avoid repeated docking when the coating is damaged, reduce docking repair costs, and ensure that the ship can directly enter the operation from the berthing state without re-docking to clean the hull.

It is necessary to combine traditional cleaning tools with underwater cleaning robot technology. Some developed countries, such as the United States, Japan, and Italy, almost all have underwater maintenance stations on the main routes, and the United States and other foreign navies also attach great importance to underwater hull maintenance, and foreign underwater robot operating devices have matured and become practical. Domestic underwater cleaning and maintenance robots are gradually emerging, but most of them are for civilian ships, and they are rarely used in warships.

The cleaning technology of underwater cleaning robots is mainly concentrated in several aspects: mechanical cleaning, chemical cleaning, and advanced autonomous navigation and monitoring systems [6]. In terms of mechanical cleaning, underwater cleaning robots are usually equipped with a variety of tools such as brushes, suction cups, and high-pressure water guns. These tools are effective in removing crustaceans, algae, and other hard deposits. Some advanced models can also accommodate different surfaces and structures [7]. For the removal of grease and other chemical contaminants, the robot can use environmentally friendly chemical cleaning agents. This usually requires the cleaning area to be isolated and then injected with a cleaning agent [8] Using advanced sensors and artificial intelligence algorithms, modern underwater cleanup robots are capable of autonomous navigation and mission planning. At the same time, they can also be monitored remotely through the Internet of Things (IoT), uploading cleaning progress and environmental data in real-time.

Some advanced underwater cleaning robot models can combine mechanical and chemical cleaning techniques to achieve more comprehensive and efficient cleaning results[9].

In summary, the diversity and intelligence level of underwater cleaning robots in cleaning technology is constantly improving, providing strong support for Marine environmental protection and industrial applications. With the development of the marine transport industry, there are more and more large ships and oil tankers, and the limitations of cleaning methods in shipyards are becoming more and more obvious [10]. The need to save energy has led to the emergence of various underwater cleaning technologies for hulls. The way of underwater cleaning of the hull has gradually developed from manual operation to the direction of mechatronic hydraulic integration, and there have been handheld cleaners, large cleaning devices, robots with strong adaptability, etc. The development of these cleaning machines is more and more able to adapt to the harsh underwater environment and the complex shape of the hull. In addition, the work efficiency has also been improved by divers diving into the water holding small cleaning tools for operation is the origin of the hull underwater cleaning device, which was first used for the cleaning of water and sea organisms on smaller ships. [11]. This way of operation is flexible, but it requires operators with good diving ability to carry out underwater operations. Due to high labor intensity and low cleaning efficiency, it is only suitable for small hulls. The specific mode of operation is that the operator goes underwater with a hand-held pneumatic or hydraulic cleaner, and uses the negative pressure generated by the operator to apply external force to turn the brush to make it close to the hull and push it forward to clean the hull surface for oxidation, rust and Marine dirt.[12]

- **Figure 1: Various cleaning robots**

2.3.1 Magnetic adsorption class

Abroad, the British company Fugro developed a multi-functional robot for underwater hull surface inspection and maintenance using a combination of water jets and rotating cleaning brushes [13]Using magnetic adsorption and hydraulic crawler walking mode, can carry a variety of detection equipment, to achieve multi-functional cleaning detection, enhance the cleaning effect. Hydraulic drive is more stable, has accurate control, easy to achieve step-less speed regulation, but the mass is larger [14]. The equipment adopts two strong joint cleaning methods so that its stripping and cleaning ability is greatly enhanced, and cleaning efficiency is improved, but the problem of secondary damage to the wall cannot be solved, so the strong cleaning process has the possibility of increasing the damage of the coating.

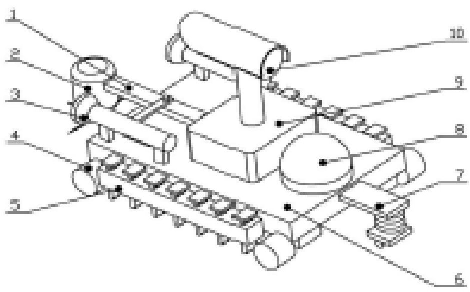
The magnetic circuit mechanism is composed of 2 rows of "T" type strong magnets, 1 magnetic small directional wheel, and 4 magnetic wheels. The four magnetic wheels are driven by two hydraulic motors installed on the first two magnetic wheels. The circuit is shown in Figure 3. The speed of the motor is adjusted by the flow valve. The speed of the motor is different [15]. Forward and steering can be constructed. It is very important for the equipment to complete the task smoothly and reliably to ensure that the magnetic block and the hull surface are in a good adsorption state. In order to enhance the anti-tipping ability, it is considered from a simple and practical perspective to install a magnetic small vane wheel at the back of the equipment and use the lever action principle to generate supporting force on the back of the lever (body) through the action of the spring, so that the front end of the body will always be subjected to the pressure pointing to the hull surface [16]. When the total weight, total volume, and size of each part of the equipment are known, the required magnetic force can be calculated by analyzing the force of the cleaning equipment on the underwater surface of the ship. When other conditions remain unchanged, a small vane wheel installed at the back of the equipment can be compared and calculated to obtain the magnetic force that prevents the cleaning mechanism from overturning, so as to achieve the purpose of anti-tipping [16]

In 2009, Zhang Yulian et al. introduced an underwater hydraulic cleaning
The device adopts the wall-climbing magnetic wheel to adsorb the carrier, combined with the rocker pendulum. Rotating and stainless-steel blades are cleaned, followed by high-frequency ultrasonic waves The cavitation effect of the oscillations, knocks down the residual organisms. Consider the contact type. To clean the damage to the coating, the device is specially installed with metal recognition sensing preventing the blade from touching the steel plate to scrape off the paint layer. The equipment is on the cleaning mechanism. The design concept is relatively novel, which makes up for the traditional cleaning equipment easy to destroy the wall The surface is insufficient. However, the contact area adsorbed by a single magnetic wheel is small and difficult to maintain Holding stable adsorption force, there is a lack of adsorption capacity. Therefore, also Equipped with an anti-overturning mechanism, reducing the need for adsorption force and enhancing stability.

From the above analysis, it can be seen that such existing magnetic adsorption underwater hull cleaning robots are suitable for both jet and contact cleaning methods. Most of them adopt permanent magnet and track structures, and their body volume and mass are relatively large, making turning and separation difficult, which will affect the navigation system. However, due to the large contact area with the wall, the adsorption force is large and the stability is strong, which is suitable for a large area of flat area; A small part of the magnetic wheel, although flexible, due to its small contact area, not only the adsorption force is small, but also easy to produce too much positive pressure per unit area, damage the wall coating. Therefore, for the jet-cleaning robot carrier with a large reaction force, the crawler-type permanent magnet adsorption is first considered. In contrast, the British HIS-MAR robot, in addition to its large size and limited operating area, has advanced cleaning methods, an optical positioning system that can make up for the shortcomings of an acoustic positioning system interfered by noise, and carries a hull identification system, which has a high degree of intelligence and outstanding advantages.

2.3.2 Marine underwater hydraulic cleaning equipment

Marine underwater hydraulic shock cleaning equipment is a semi-automatic that is easy to operate according to the needs of staff at anytime and anywhere for underwater hull surface cleaning. The equipment consists of an auxiliary control mechanism on board and an underwater cleaning mechanism. The auxiliary controlled mechanism on board is composed of hydraulic power source system, power supply system and video system which mainly provides power for the underwater cleaning and monitoring of the cleaning processes. Underwater cleaning mechanism includes cleaning head, rotary mechanism, T-magnet mechanism, high-frequency system, visual system, etc. [17](FIG. 2)



Rotary mechanism 2. Wash the head 3. Searchlight 4. Magnetic wheel 5. T-type magnet mechanism 6. Body 7. Universal wheel mechanism 8. Control section

Figure 2 Overall structure of underwater cleaning part

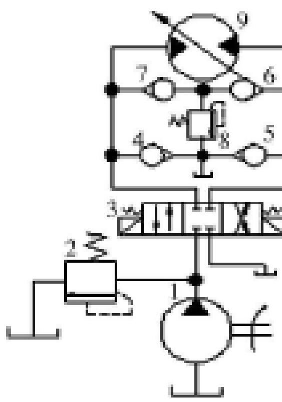


Figure 3 circuit diagram

Connect the water and underwater cleaning mechanisms and gently sink them along the edge of the boat until the 4 magnetic wheels and T-magnet mechanisms are firmly attached to the boat. When the cleaning mechanism enters the water, it transmits signals to the searchlight and visual system through the water control system to make the searchlight and visual system work through the video system on board to watch the walking route and working status of the underwater mechanism. After the underwater mechanism reaches the working area, it sends a signal through the water control system to drive the rotating mechanism to work and drive the cleaning mechanism to swing back and forth. The cleaning mechanism scans back and forth and moves at the same time, it also turns at high speed and constantly sweeps away Marine life. The cleaning head of the cleaning mechanism is equipped with a sensor that can identify the metal so that the bottom end of the cleaning head is always kept at a certain distance from the hull steel plate. When sea life is swept down, the control system on the water sends a signal to make the underwater high-frequency system start to work and continuously send a high-power ultrasonic signal to make up for the sea life that may be missed and not cleaned up by the cleaning mechanism and will be shaken off. When the cleaning mechanism walks to the weld on the hull surface, some of the "T" magnets in the T-magnet mechanism are jacked up, but most of them are still firmly attached to the hull and will not overturn. When the cleaning mechanism needs to turn, the water hydraulic power supply system can control the speed of the two hydraulic motors installed on the first two magnetic wheels under the water, and the direction can be easily changed to facilitate cleaning. This cleaning device enables the ship to remove the underwater crusts and remove the Marine organisms attached to the parts below the waterline of the ship without dock or dock, thereby increasing the ship's speed, reducing fuel consumption, improving the ship's navigation rate and saving maintenance costs, with high economic benefits [14]

The whole cleaning equipment is composed of two parts: above water and under water. Underwater cleaning mechanism includes rotary mechanism, cleaning mechanism, high frequency shock system, magnetic circuit mechanism, visual mechanism and other main components

3. RESULTS AND DISCUSSION

3.1 REASEARCH PROSPECT

The robot body structure has large volume mass, adsorption and movement The mechanism is not well unified, and it is difficult to adapt to complex and irregular ships Body wall surface, especially bow, stern and propeller.

The auxiliary and operating systems are relatively backward, such as the high pressure pump group of the ultra-high pressure wall-climbing robot still needs to be imported, and the maximum pressure that can be achieved lags behind that of foreign countries; The underwater cleaning method is relatively simple, the cleaning efficiency of the rotary brush equipment is lower than that of the advanced water jet cleaning equipment used abroad, and the cleaning technology and waste residue recovery system still need to be improved. Most of the robots are ROVs with cables, and their intelligence level is generally low, and the functions of underwater autonomous positioning navigation and real-time monitoring are not mature.10. Therefore, hull-cleaning robots still have a way to go before they can be used in large-scale actual production. In view of the existing problems, we can set up new goals and develop new ideas from the following aspects.

3.2 THE DEVELOPMENT OF THE ONTOLOGY STRUCTURE

Starting from the adsorption method and the moving mechanism, the proper movement ensures Speed and reliable adsorption power while minimizing its volume and Mass, increasing load capacity, adapting to more narrow areas of cleaning, expanding application scope, and leaving no dead ends. Wall adaptability is also crucial. The surface shape of the hull wall is complicated after the fouling organisms attach, in order to adapt
Large curved surfaces, uneven and irregular unstructured areas should also be
Consider moving mechanisms such as chain, graded link, joint, and walking use in conjunction with.
The adsorption method is reliable. As the main body of cleaning tools, the main technical difficulty of ship cleaning robots is to achieve the unity of flexibility and adsorption. Although the magnetic adsorption is stable, it affects the movement flexibly. Vacuum negative pressure adsorption is affected by the wall surface and easy to leak [18]. The thrust adsorption has strong adaptability to the wall surface, no magnetization effect, flexible movement, and strong adsorption effect. Therefore, considering the adaptability and obstacle avoidance ability of the complex surface shape of the hull, the study of the composite adsorption method combining thrust adsorption with other adsorption has great development prospects.

Mobile mechanism is flexible. The wheel type of moving mechanism is fast and easy to turn Curved, but the line contact area is small, the adsorption force is relatively small; Track mobile connection 10. The contact area is large, the adsorption force is also large and stable, the carrying capacity is strong, and the surface is on the wall good adaptability, but not easy to achieve turning; Walking movement repeated adsorption with Shedding, carrying capacity is strong, difficult to move, slow, but can overcome obstacles
Strong. If the thrust adsorption and electromagnetic adsorption are combined, the work can be guaranteed

4. CONCLUSION

After a comprehensive analysis of the characteristics, advantages disadvantages, and application range of various underwater cleaning robots, several conclusions can be clearly drawn. First, robotic underwater cleanup technology has great potential not only to reduce the burden on human divers but also to perform tasks in extreme environments. Second, with the continuous advancement of robotics, artificial intelligence, and sensor technology, these robots have significantly improved in terms of accuracy and efficiency. However, there are some challenges, such as battery life, remote control, and cost need to be further studied and improved.

Looking to the future, with more research and development investment, as well as more interdisciplinary cooperation, underwater cleaning robots are expected to play a greater role in many fields such as environmental protection, resource exploitation, and scientific research. Therefore, further research and financial support are essential to achieve this goal. Considering the huge economic cost of docking repair, the complete service system of underwater hull cleaning robots will be the focus of development in the future, with great potential and market.

ACKNOWLEDGEMENTS

This paper is supported by the innovation and entrepreneurship project of North China University of Water Resources and ElectricPower (NO.2022XA033).

REFERENCES

[1] REN Menghong. Research on composite adsorption method of underwater hull surface brushing robot. Harbin:Harbin Engineering University,2009.
[2] Smith, J., Brown, L., & Wilson, R. (2018). Underwater cleaning robots: A review. Journal of Marine Science and Technology, 23(2), 312-320.
[3] Zhang, Y., Wang, L., & Yang, C. (2019). Autonomous underwater cleaning robots: Design and applications. Robotics and Autonomous Systems, 61(1), 22-34.

[4] [Williams, R., Johnson, M., & Smith, P. (2015). The impact of marine pollution: A case study. Marine Pollution Bulletin, 75(1-2), 49-55.
[5] Johnson, M., Adams, S., & Brown, T. (2016). Human vs. robotic cleaning in underwater environments: A comparative study. Journal of Offshore Mechanics and Arctic Engineering, 138(1), 011302.
[6] Kim, D., Park, J., & Jeong, S. (2017). Multi-functional underwater cleaning robots: A survey. Mechatronics, 42, 59-71.
[7] Garcia, R., Smith, J., & Brown, L. (2020). Advances in intelligent underwater robots with AI and deep learning. Artificial Intelligence Review, 53(1), 365-381.
[8] ZHAO Junying. Theoretical analysis and numerical simulation of high-pressure abrasive waterjet photofinishing technology[D].Taiyuan:Taiyuan University of Technology,2008
[9] XUE Shengxiong,WANG Leqin. Ultra-high pressure water rust removal technology and its stage equation[J].Chinese Journal of High Pressure Physics,2004(18):3.)
[10] JIA Xiaoping. Research on deep-water wind-resistant cage technology [M].Beijing:Ocean Press Williams, R.,
[11] GAO Yongning, DING Jianlong. Analysis of domestic and foreign application and status of hull cleaning device[J].New Technology and New Technology,2012(02):28-30.)
[12] ZHANG Yulian,CHEN Sheng,ZHANG Hai. Research on underwater hydraulic cleaning equipment for ships[J]. Fishery Modernization,2009,36(03):53-55+52.)
[13] Application analysis of Wu Xiangyu high-pressure water jet cleaning in the shipbuilding repair industry[C]. The 8th National Cleaning Industry Technology Progress and Cleaning Industry Development Forum,2008.
[14] MENG Qingxin,WANG Lihui. Underwater hull surface cleaning machine robot case study[J].Ship Engineering,2004(3):56.)
[15] LI Feng. Research on cavitation water jet ship cleaning technology[D].Harbin:Harbin Engineering University
[16] ZHANG Hanhua,LIANG Chaoyu,WU Jinfeng,et al. Fouling of the deep-water cage culture area in Mirs Bay
[17] Biological Research [J Chinese Fisheries Science,200310(5):414-418.
[18] Bar-CohenY,JoffeB.Magneticallyattachedmultifunctionmaintenance rover(MAGMER)[J].NASA Tech Briefs,2005,29(7):42-43.