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Research Article

Design and Development of Underwater Radioactive Material Cleaning Robot Applied in Pressure Vessel

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Abstract

This paper designed and developed an underwater robot for radioactive material cleaning and other operations, instead of manual methods. Since radioactive substances exist in a pressure vessel, the interior of which is filled with water, and the working environment of the robot is underwater. Its working method is as follows: the inner wall of the pressure volume is cleaned by the cleaning and grinding tools mounted on both sides of the fuselage, and the radioactive material dropped from the bottom of the pressure vessel is cleaned by the robotic arm mounted on the bottom of robot. At the same time, sensors such as cameras, thermometers, and sonars mounted on the robot can return video images and information data inside the pressure vessel. Under the nuclear environment, the underwater robot can improve the cleaning efficiency of the inner wall of the pressure vessel, and reduce the radioactive radiation received by the staff, and control the production of secondary and tertiary wastes. The test results show the effectiveness and practicability of the underwater robot, meanwhile the robot can also be used for cleaning up other underwater radioactive environments.

Keywords: Underwater Robots; Radioactive Cleanup; Pressure Vessel Cleaning; Dynamic Simulation; Hardware Selection

Introduction

In recent years, since robots can perform some repetitive and dangerous tasks, and some tasks that require high precision and high intensity cannot be completed by humans, industrial robots have been rapidly developed and widely used. For example, grinding robots [1,2], loading robots [3,4], maintenance robots [5], cleaning robots [6], cutting robots [7], etc. Especially, it has become more and more common to use robots in some dangerous or constrained environments, such as, Paez [8] focused on the navigation of a swarm of robots that can avoid collisions with obstacles and tackled the problem of finding victims in a search and rescue environment. Tang [9] proposed a GWO-based multi-robot in unknown environment, which can perform its superior in both static and dynamic target searching. John [10] investigated the used of a Virtual Reality digital twin under transmission both human and robot with unpredictable accidents happening. Zhou [11] proposed an improved algorithm for nuclear robot path optimization under the dual constraints of distance and radiation in the radiation environment, which shows more reliable and converge faster. Three sensors namely: Colour-Depth cameras, Light Detection and Ranging, Millimeter-Wave RADAR, interest in the robotics. This paper concluded with a performance comparison and discussed the possibility of combination for mobile robot localization for nuclear facilities [12].

As a clean and economical energy, nuclear energy has been widely used in military, medical, industrial, and other fields [13-15]. When a nuclear reactor is used and developed, it will inevitably enter the stage of maintenance, refueling or decommissioning [16]. There is a risk of radioactive contamination when handling these stages. At present, reactors such as experimental research reactors, military reactors, and power generation reactors need to be repaired, refueled, or decommissioned. In the maintenance, refueling and decommissioning technologies of nuclear reactors, the key is to remove the radioactive contamination on the surface of relevant facilities, equipment, and materials to prevent which ensures the safety of the external environment and personnel [17]. As a radioactive material barrier that contains the core and withstands irradiation, the structural integrity of the pressure vessel is of great significance to the safe operation of the reactor. Therefore, in the process of repairing, refueling, and decommissioning of nuclear plants, we need to clean and decontaminate the pressure vessels [18]. Visual inspection is then performed to determine whether there are cracks, defects, etc., to ensure the integrity of the pressure vessel. When cleaning the interior of the pressure vessel, a common method is manual ultrasonic cleaning. However, the manual use of ultrasonic cleaning has the following problems: First, the pressure vessel contains many radionuclides, and manual cleaning or manual cleaning will inevitably be exposed to a large amount of radiation; second, the pressure vessel is large and has a certain height. The presence of corrosion products, screws and other falling materials can be difficult to clean. In addition, during the cleaning process, it is also necessary to ensure that the workers are exposed to as little radioactive radiation as possible, the environment is subject to as little radioactive pollution as possible, and the principle of generating as little secondary waste as possible and controlling the amount of three wastes.

According to the above work requirements, a tool that can replace manual cleaning and inspection of pressure vessels and can efficiently solve related problems becomes particularly important. During the use of nuclear reactors, radioactive waste will be produced such as radioactive fuel, wastewater, waste gas, waste, etc. The management and disposal of related radioactive products occur a serial of difficult problems. The nuclear environment working robot is a special robot used to solve such problems. According to relevant information, nuclear environment operation robots include: ODEX-I robot and upper Scavenger applied in Three-Miles Island [19], which are used for accident site monitoring and radiation site disposal. Mobot-ChHV robot and Pioneer robot used in Chernobyl [20] for radioactive material cleaning and environmental monitoring. Robots (A-robot, B-robot, RESQ-A, RESQ-B, RESQ-C) applied at Japan Nuclear Fuel Conversion for on-site monitoring and radiation disposal. Robots (Pack Bot, Warrior, Brokk90, Mini Manbou, Meister) used in the Fukushima nuclear disaster [21] are used for radiation area detection and on-site disposal.

It is important to design and develop an underwater robot with corresponding working ability to clean the inner wall of the pressure vessel by replacing the manual cleaning method, pick up the falling substances such as corrosion products and screws from the bottom, and manipulate the robot to move in various directions underwater, which are equipped with cameras, thermometers, sonar, etc. to return the information data inside the pressure vessel. This paper has been organized in six sections. The overall program design and research is presented in Section 2. Section 3 describes the functional design and simulation for underwater robot, include in propeller, control cabin, shape, and structure. Hardware system is designed and applied in Section 4. Experimental verification part is shown in Section 5. In last section, conclusion, and future work.

Overall program design and research

This paper aims to design a robot for cleaning and testing nuclear reactor pressure vessels, such as cleaning the inner wall of the pressure vessel and picking up radioactive materials at the bottom, and at the same time transmit images and information data inside the pressure vessel. By manipulating and controlling the robot, the underwater staff can complete various predetermined actions.

The design requirements and goals of underwater robot

The cleaning robot needs to meet the functions of underwater work and movement, so the design goal of this topic is the underwater cleaning robot. Considering that the robot will be affected by water pressure when working underwater, the conservative value of the water depth inside the pressure vessel is considered as 5 meters. When manipulating the robot to perform tasks, such as underwater movement, internal image transmission, and cleaning operations, it is necessary to design the relevant systems and parameters for the robot, and the robot is required to have the smallest possible volume and weight. To sum up, the main qualitative design parameters of the underwater robot are as follows in Table 1. According to the task of the underwater robot in this subject, the overall system design is divided into modular units. it is necessary to consider the distribution of space to ensure the overall coordination and working ability of the robot. The design goals of underwater robots are mainly expressed in the following aspects:

Table 1: The main qualitative design parameters.

Requirements	Parameters
Maximum working water depth	5 meters
Maximum external dimension	800mm*800mm*800mm
Overall maximum mass	30 kg
Image system	Underwater high-definition camera
The fastest speed	2 knots
Communication system	Optical fiber communication or wire-less communication
Power supply system	DC power supply or AC power supply
Cleaning task of the inner wall	Design a physical brush for cleaning
Picking task at the bottom	Picking up by the robotic arm

a. The overall layout compact, which improves the utilization rate of space.

b. Stability and balance to ensure the overall performance during work.

c. Certain anti-radiation ability and can work normally in the radiation environment.

d. The comprehensive working ability, so that the robot is equipped with multiple modules to have multiple cleaning functions.

e. Reserve equipment space, and flexibly install relevant detection equipment according to the target tasks of the underwater robot.

f. Safe and reliable. When controlling the work of the underwater robot and issuing instructions to the robot, ensure that the robot completes the predetermined actions according to the instructions.

The design scheme of underwater robot

This part mainly discusses and studies the design ideas of the overall scheme of the underwater robot. Proposing a feasible scheme according to the actual situation and using the SolidWorks software to design and model the shape of the robot. The modeling idea of underwater robot is shown in Figure 1.

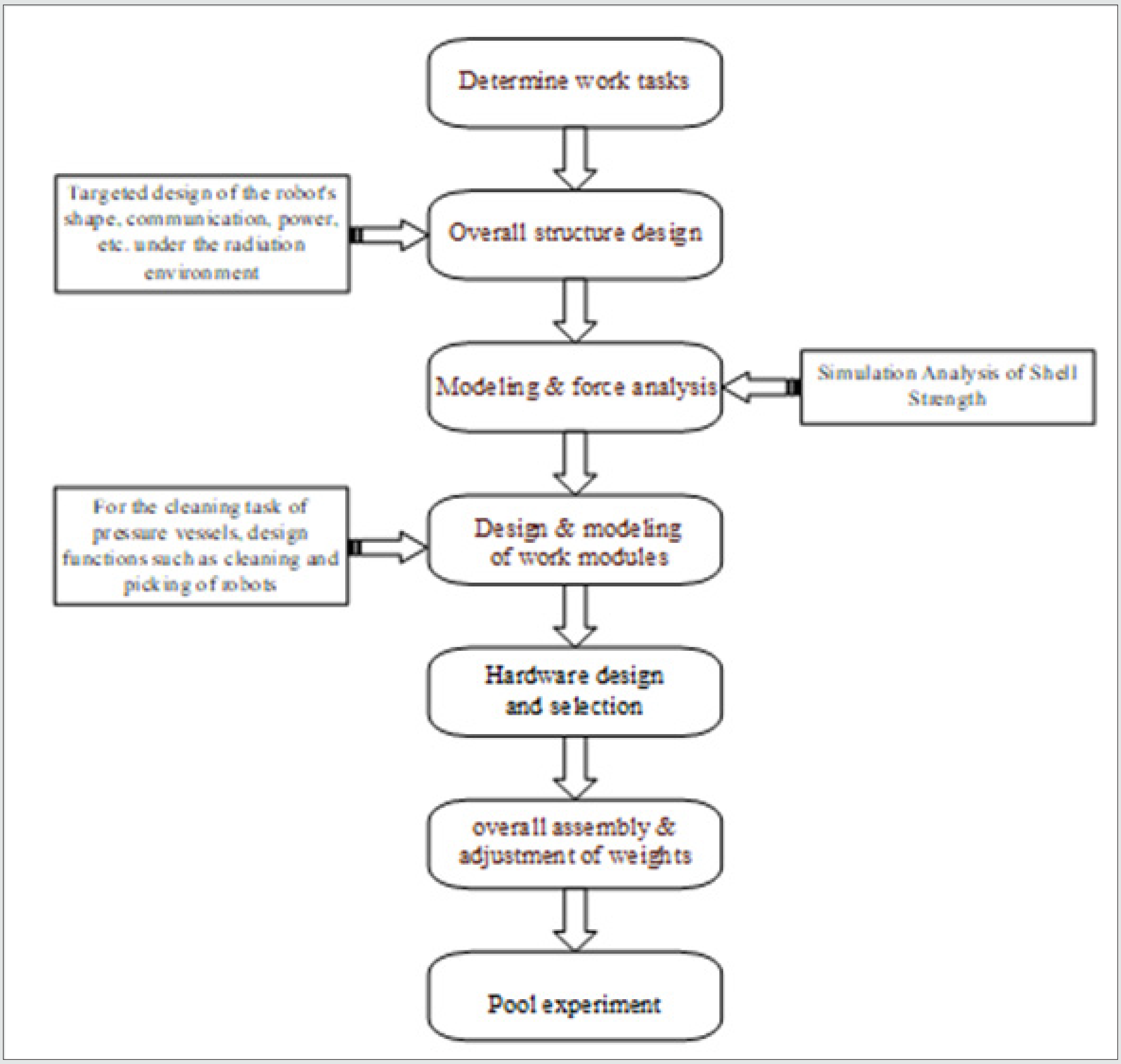

Figure 1: The graph of design flowchart of underwater robot.

Shape structure scheme

There are great differences in the shape, structure and size of underwater robots according to different applications and environmental conditions. Considering the working environment, required modules, work tasks and other factors, and to minimize the resistance when working in water. Therefore, the shape of the underwater robot adopts a flat shuttle design, which has the following advantages

a) The fluid resistance received during underwater movement is small, which can improve the movement performance

b) To meet the compressive strength requirements when the water depth is 5m to the greatest extent

c) The usable space is large, which is convenient to carry equipment and instruments according to actual needs.

The shape of the underwater robot is designed based on the initial stability and anti-sinking algorithm, and the shape adopts a flat shuttle design to produce better propulsion effect and drag reduction effect. The flat shuttle-shaped design also makes the structure firmer and improves the pressure resistance and stability of the underwater robot. It is convenient to carry various instruments and working modules, including various sensor components, underwater thrusters, robotic arms, core cabins, etc. The shape and structure of the underwater robot can be modeled by SolidWorks software as shown in Figure 2.

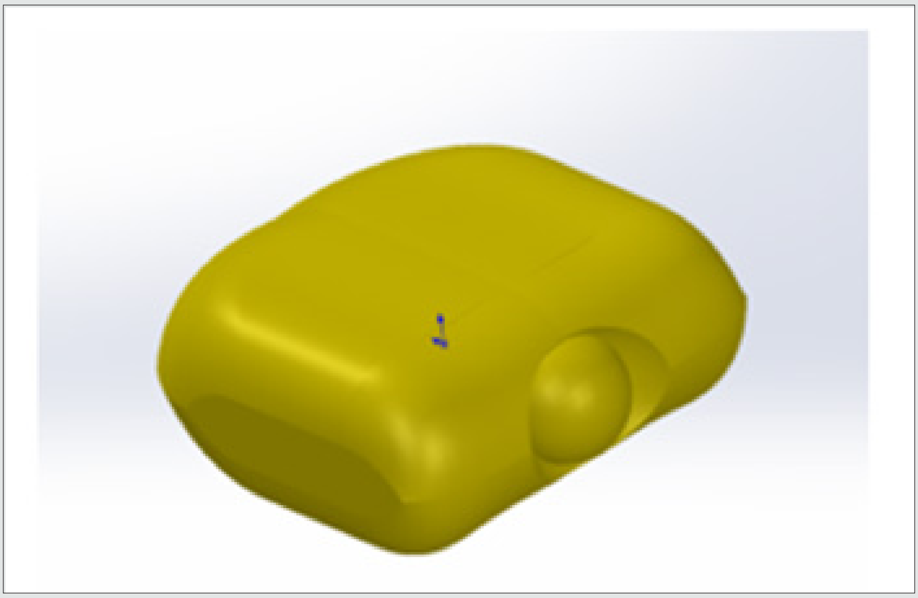

Figure 2: Shape modeling.

Power supply scheme

The underwater robot tail is designed with umbilical cord, and there are three work aspects:

a) Power can be supplied to the underwater vehicle by the remote-control terminal

b) Data transmission of image and information between the remote-control terminal and the underwater robot

c) It has good resistance to pulling and placing the underwater robot.

Currently, the types of underwater power transmission are mainly divided into DC and AC. DC has obvious advantages, such as long distance of power transmission, large transmission power, small line loss, high system stability, and small communication interference. When DC is used, it needs to be converted by 220V or 380V DC through a special device or module before it can be applied.

Communication system scheme

The underwater vehicle needs not only motion instructions from a remote-control terminal, but also image video and information data upload. Generally, there are two main transmission modes of umbilical cord cable: coaxial cable transmission mode and optical cable transmission mode. When coaxial cable transmission is used for long distances, it is often interfered by various factors of environment. What's more, optical composite cable is a composite of DC power supply cable and optical communication cable. It can satisfy the functions of power supply and communication and avoid cable entanglement due to complex lines. Moreover, optical fibers have excellent communication rates and data transmission capabilities. Optical fiber communication can greatly improve the transmission effect and communication rate of video images., the loss of optical fiber is small even in long-distance data communication and transmission with strong anti-jamming ability. Considering the actual working requirements of the underwater robot, the optical composite cable transmission mode is used in this communication scheme. The structure of the optical composite cable is shown in the Figure 3.

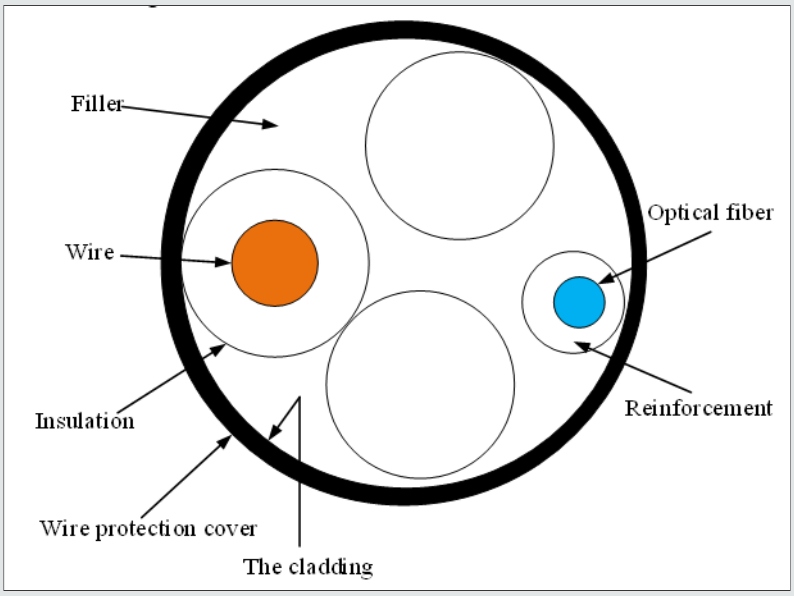

Figure 3: Structure diagram of optical composite cable.

Work module design scheme

Cleaning grinding disc

When cleaning the inner walls of pressure containers, it is necessary to carry specific tools such as brushes or other physical machines to use. Therefore, a rotating cylindrical cleaning disc with a diameter of 120 mm and a height of 208 mm is designed on both sides of the front of the underwater robot. Each disc can be loaded with 8 cleaning and grinding bars. The cleaning grinding strip is made of rubber and corundum which is poured at high pressure in a certain proportion. It has soft, medium and rigid properties and can be replaced at any time. The grinding strip is fixed on the cleaning disc, and the high-speed rotation of the grinding disc drives the movement of the grinding strip to achieve the cleaning function of the inner wall of the pressure container, as shown in Figure 4.

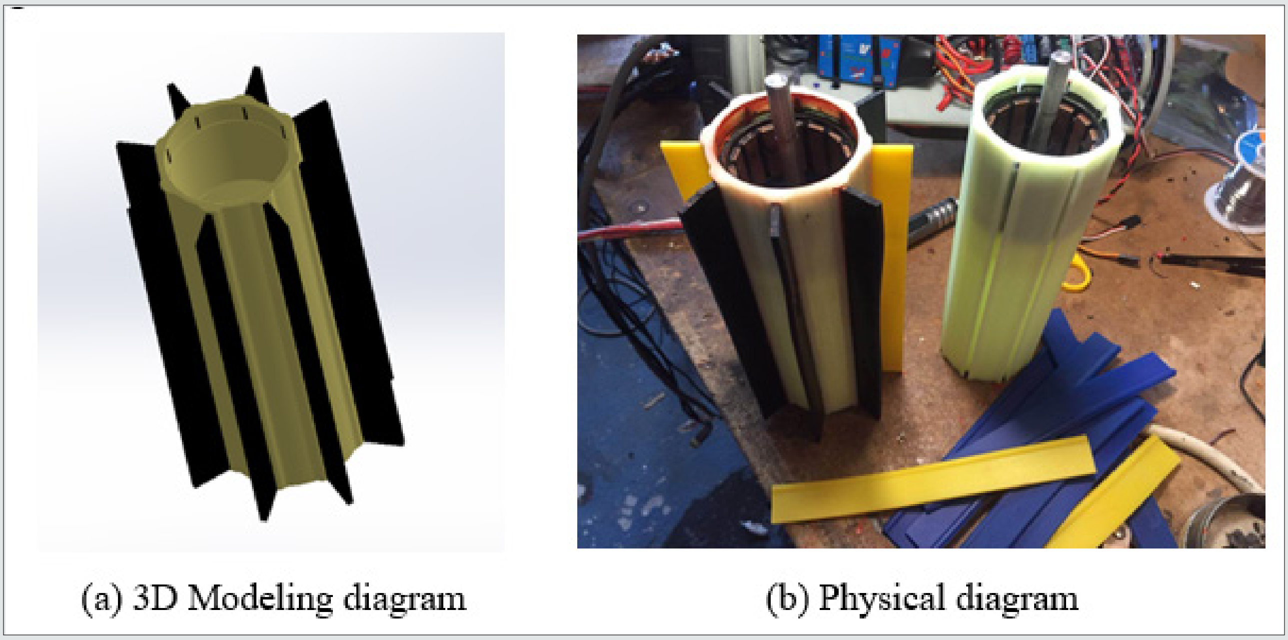

Figure 4: Example of cleaning grinding disc.

Manipulator

The underwater robot needs to grab and clean the residues at the bottom of the pressure vessel, such as corrosion products, screws, etc. Considering that the corrosion products at the bottom of the pressure vessel may be irregular in shape, and it is difficult to clamp the conventional arm. Therefore, a biomimetic flexible manipulator is used. Biomimetic flexible manipulator is made of flexible materials with high flexibility and complex shape adaptability. The rigid manipulator become a flexible manipulator which can adjust its shape and bounce back quickly at the same time from originally a limited degree of freedom. The grabbing state is shown in Figure 5.

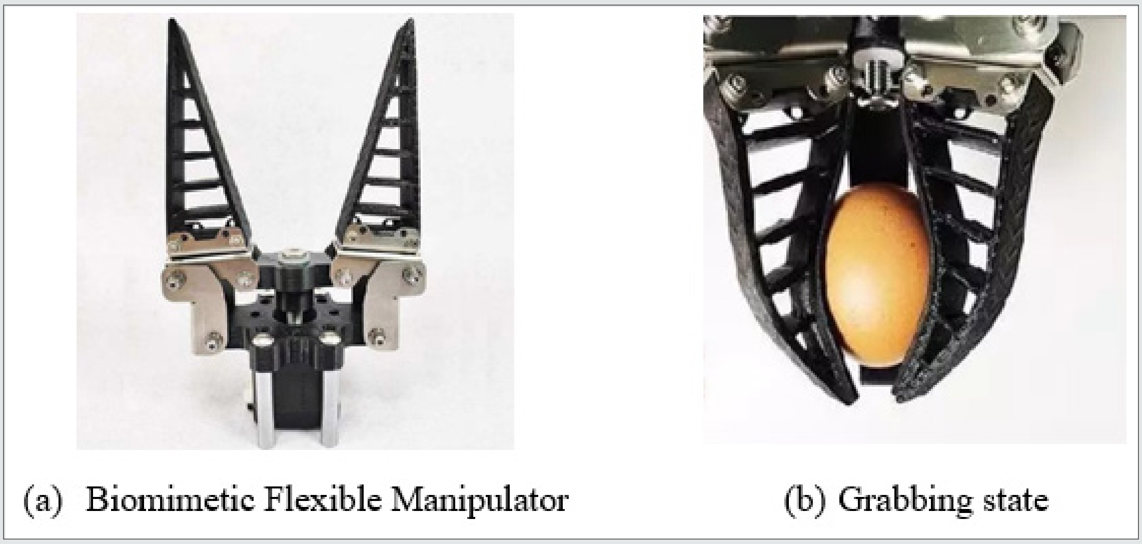

Figure 5: Graph of manipulator.

The underwater vehicle may encounter some special cleaning situations during its operation, such as encountering large objects at the bottom of pressure containers, or sticking to the bottom of pressure containers, which makes it difficult to grasp. Meanwhile, there are some difficulties in the design and assembly of a variety of tools, such as switching tools and adjusting the orientation of tools. Therefore, the innovative design of a 360o rotatable multi-functional operation platform on the bottom of the underwater robot as shown in Figure 6. The multi-functional platform is designed as a triangular star with three extension axes. At the end of the extension axle, there are three types of tools: mechanical arm, sawing disc and drill bit. Compared with the traditional single function carrying module, the multi-function operation platform can achieve the integrated control of bionic flexible manipulator, sawpan, electric drill, cutting, grinding and grabbing of underwater objects. The flexibility and cleaning ability of the underwater vehicle are greatly improved.

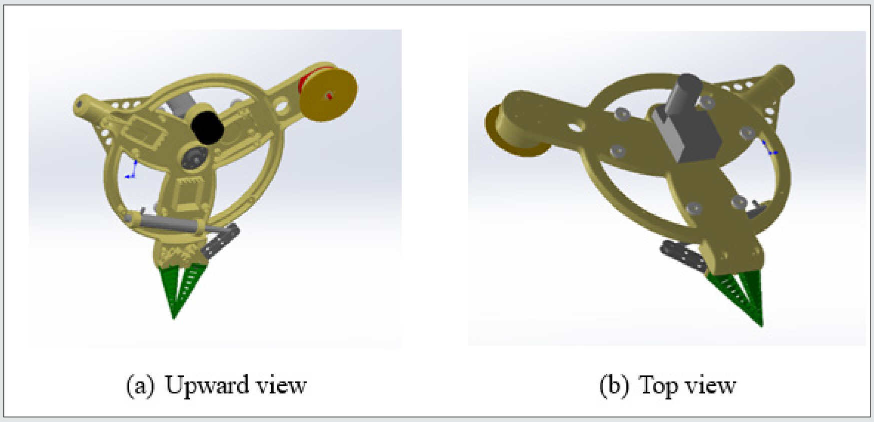

Figure 6: Multifunctional Platform 3D Model.

Functional Design and Simulation

This section will continue to refine the functional structure of the robot and improve its modules and components. At the same time, the overall gravity and the buoyancy of the underwater robot are calculated, and the water pressure and fluid resistance are simulated to verify its performance in motion and work.

Whole structure design and layout

In the structural design of the robot, the embedded structural layout is applied, which is embedded directly into the shape structure. It enables all kinds of irregular modules to be better assembled and fit in limited space. The space utilization of the robot has also been greatly improved. The various structural arrangements include the underwater propeller, control cabin, shape frame.

The underwater propeller

the vertical propeller and the horizontal propeller are the dynamic devices of the robot. The underwater propeller is modeled as shown in Figure 7, and both of them can achieve the direction and orientation change of the robot underwater.

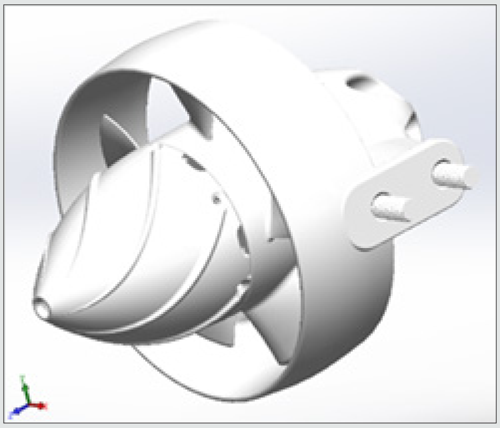

Figure 7: 3D modeling of underwater propeller.

Control cabin

To place the electronics of the underwater robot and lay it inside the robot according to the reasonable shielding design. The control chamber model is shown in Figure 8.

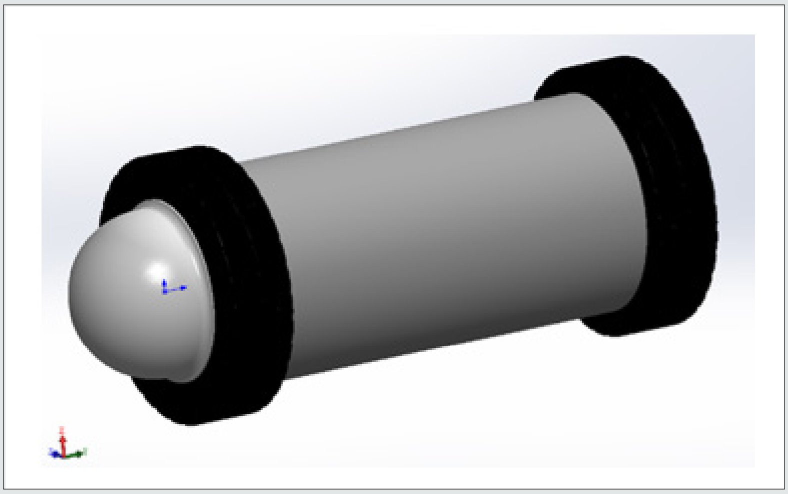

Figure 8: 3D modeling of the control chamber.

Shape frame

The frame bears pressure on the underwater robot mainly and contains a serial of control modules. Embedded shape design as shown in Figures 9 & 10.

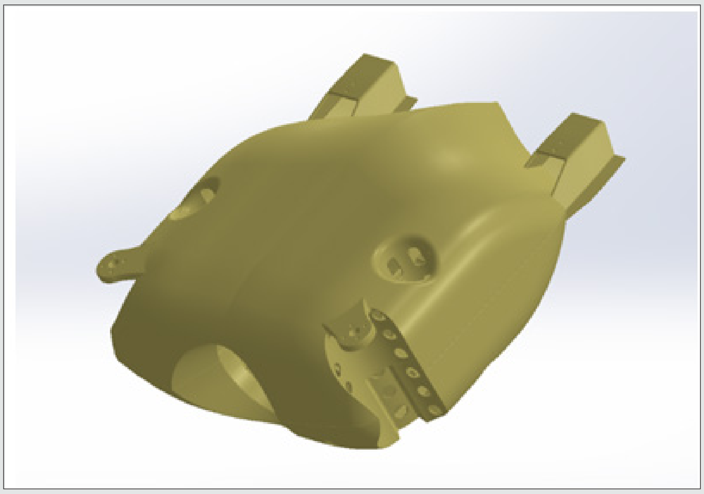

Figure 9: Embedded shape frame design.

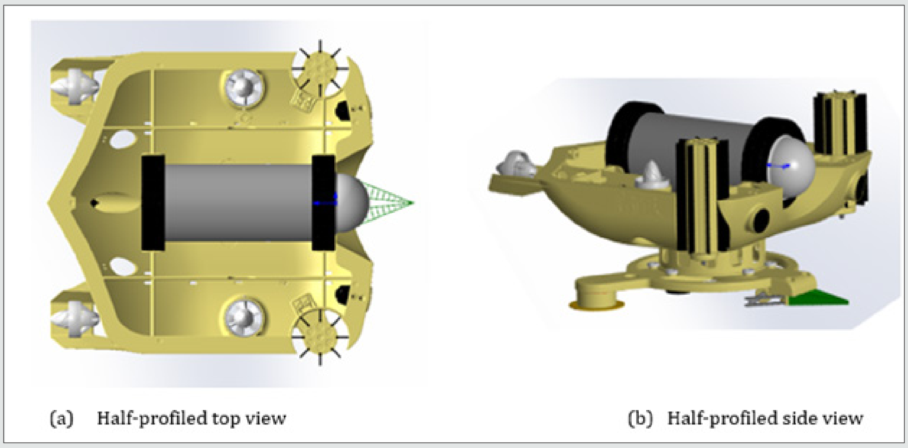

Figure 10: Layout of underwater robot**.**

Overall structure

The underwater robot uses left and right symmetrical structure and adjusts the force balance of the vehicle through simple simulation calculation to ensure the stability of the operation. In the process of designing and laying out the components of each module, the stability of the robot during its movement and operation is also considered. The embedded structure of the robot is shown in Figure 11.

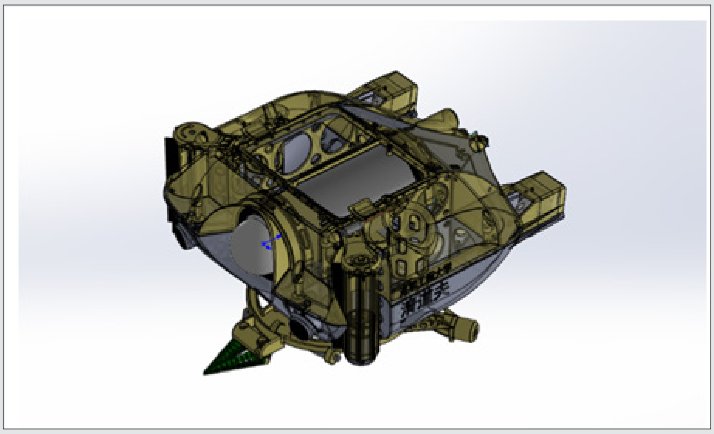

Figure 11: Embedded structure of underwater robot.

Global balance calculation and dynamics simulation

Global balance calculation

When the underwater robot is in motion and operation, it needs to keep its own stable state to avoid such situations as rollover and tilt. Requirements that the floating center and center of gravity of the underwater vehicle are on the same vertical line, so that the buoyancy and the overall weight of the robot can offset each other. After a simple mass analysis by SolidWorks software, the robot's weight is 332 mm from the tail. Floating center position can be calculated in equation (1):

$$Z_c = \frac{1}{v}\int_{-\frac{L}{2}}^{\frac{L}{2}} Z_w \, w\mathrm{d}x = \frac{1}{v}\int_{-\frac{L}{2}}^{\frac{L}{2}} (wT - S)\mathrm{d}x \quad (1)$$

Where L denotes length of vehicle, V denotes the drainage volume underwater. And (wT-S) means Floating Center Function Curve of Underwater Vehicle, by which accordingly the high stability is 67.3 mm.

The whole qualities consist of shape housing, multi-functional platform, control chamber, grinding disc, propellers and other types of measurement sensor. Each parts qualities are shown in Table 2.

Table 2: Each parts qualities exhibition.

Part name	Quality (kg)
Shape housing	14
multi-functional platform	3
control chamber	4
grinding disc	3.5
propellers	2
Other types of measurement sensor	2

The whole qualities G:

$$G = mg = 279.3N \quad (2)$$

The buoyancy is mainly caused by the drainage volume of the shell and the buoyancy material, and the buoyancy F1:

$$F_1 = \rho_w g V_1 = 294N \quad (3)$$

The difference between gravity and buoyancy is ：

$$\Delta F = F_1 - G = 14.7N \quad (4)$$

According to this difference, the balance of the underwater vehicle can be adjusted by changing the additional counterweight of the underwater vehicle, when iron block is used, the required weight mI and volume VI:

$$m_I = \Delta F / g \quad (5)$$
$$V_I = m_I / \rho_I$$

The balance between gravity and buoyancy can be kept by adding a cube iron block with side length of 5.75 cm and mass of 1.5 kg on the plumb line of the robot's gravity center.

Dynamics simulation

The pressure and resistance of the underwater robot are simulated by SolidWorks Simulink software to simulate the water pressure and fluid resistance. When the robot works inside the pressure vessel, the maximum water depth is 5 meters, and the maximum water pressure Pw is calculated:

$$P_w = \rho_w * g * h_{\max} = 49KPa \quad (6)$$

When the underwater vehicle is working under the pressure of atmospheric pressure, the total pressure P1 is shown:

$$P_1 = P_w + P_a = 0.149MPa \quad (7)$$

The maximum speed in water vmax is expressed:

$$v_{\max} = 2knot * 0.514m/s = 1.028m/s \quad (8)$$

By importing the relevant parameters into the SolidWorks simulation solver, the pressure simulation results of the robot working in the maximum water depth can be obtained, as shown in the Figure 12. It can be seen from the shell results that when the water depth is 5 m and the reference pressure is 0.149 mpa, the maximum water pressure when the robot moves forward and backward is at the front end, and the pressure is 168pa. The maximum water pressure received by the robot during sinking and floating is at the top, and the pressure is 137 pa. By consulting the performance parameters of the lead boron polyethylene material, it can be obtained that the compressive strength is 1.3 mpa. Therefore, when we use the lead boron polyethylene material with a thickness of 3 cm as the protective shell of the underwater robot, due to the stiffness of the material performance of the underwater robot, the water pressure will not have a great impact on the performance of the robot during operation and work. Setting the underwater vehicle in the motion states of forward, backward, floating and diving respectively, When the underwater vehicle moves. The simulation results are shown in the Figure 13.

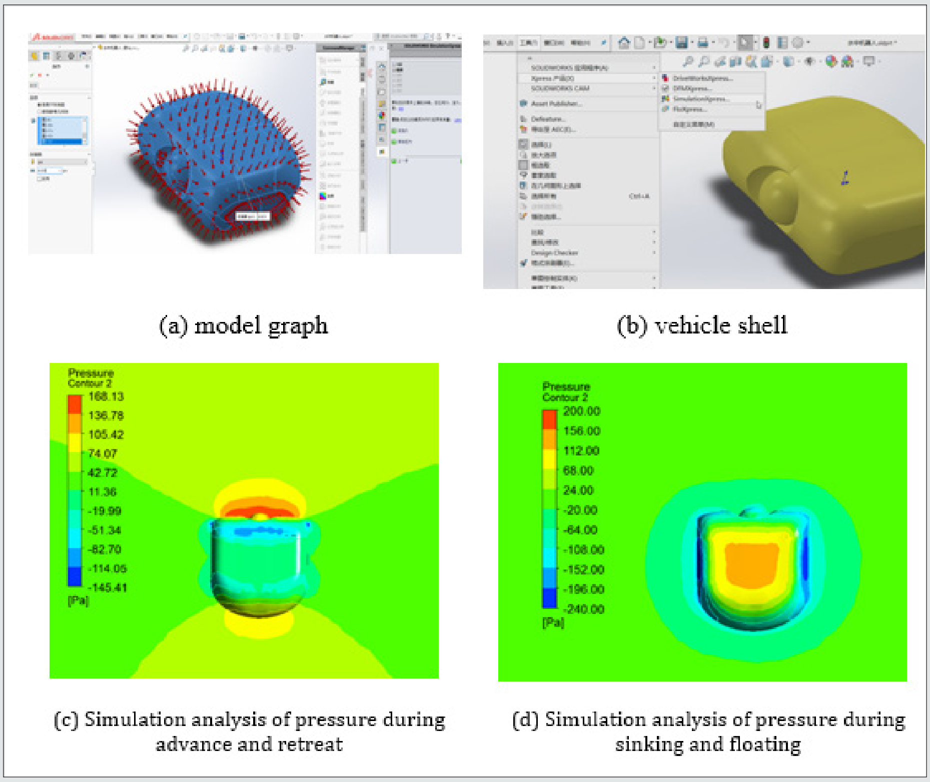

Figure 12: Embedded structure of underwater robot.

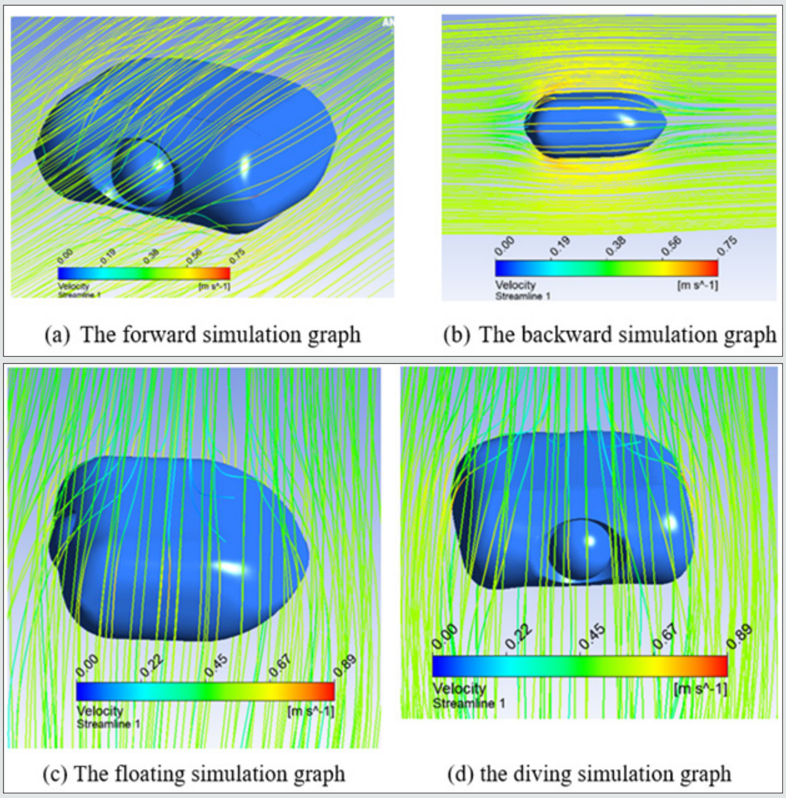

Figure 13: The motion states of resistance simulation streamline diagram.

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Hardware system design and development

The hardware system of underwater vehicle can be divided into two parts: remote control terminal and underwater vehicle. The control terminal is responsible for sending motion and work instructions to the underwater robot. The robot receives the instructions from the control terminal, makes the established actions, and returns video images and information data. This section aims to decide that the electronic devices that need to be used in motion, measurement data and signal transmission of the robot. The whole robot is composed of a remote-control terminal and an underwater part. The control system is shown in Figure 14. Those are connected through the photoelectric composite cable, which are combined with optical fiber and cable for power supply and information communication. The control terminal is responsible for sending motion and work instructions to the underwater vehicle. When the vehicle receives the instructions from the control terminal, and it responds quickly to drive each motor and realize the related functions of electric regulation.

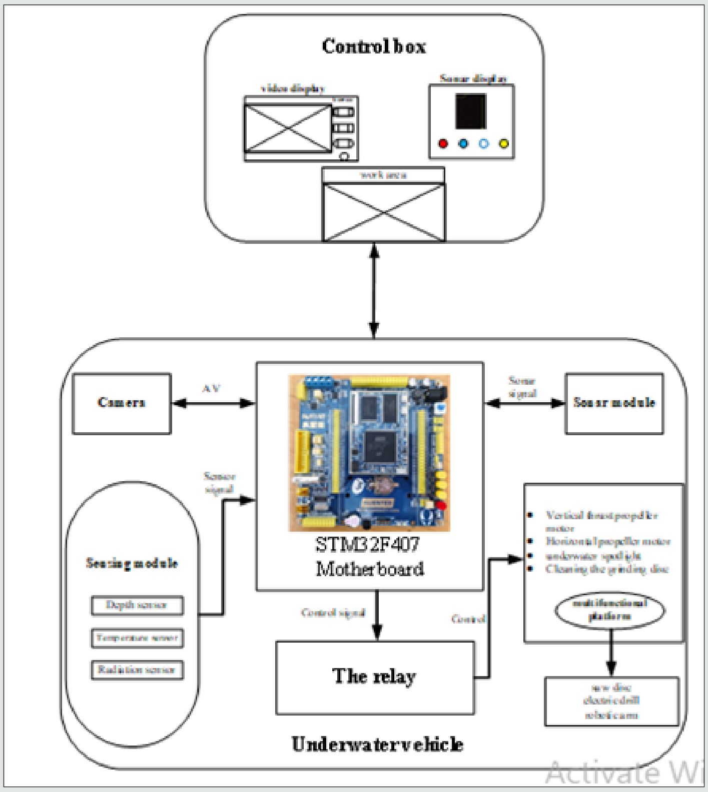

Figure 14: Design drawing of overall control system.

Control module

The control chip of the lower robot uses the STM32f407 controller manufactured by the 90 nm process of ST company, as shown in Figure 15. The controller integrates can / 485 communication interface and two RS232 serial interfaces, which is helpful for us to debug the communication system. STM32f407 controller board contains gyroscope and acceleration sensor chips and provides more than ten kinds of interfaces to facilitate the installation and commissioning of various modules, as shown in Figure 16. In the process of underwater vehicle design, the functions of autonomous recognition and autonomous work of the robot are not involved. Therefore, the robot adopts the remote-control mode. Its internal chip receives the command and signal from the control terminal through the photoelectric composite cable and realizes the command response by driving the corresponding motor.

The controller can adjust the changes of the direction and orientation of the robot by controlling the combination or separate work of the underwater thrusters from the instructions of the remote-control terminal. The process is to control and adjust the speed of the thruster motor and the ESC by PWM, so that the two vertical thrusters and the two horizontal thrusters work in combination or separately, and the water flow rate on both sides of the robot is controlled to achieve the speed of making the robot move. In terms of the communication system, the communication between the upper and lower computers adopts the RS232 serial communication interface. Due to the limitation of transmission speed and transmission distance of RS232 communication, it is necessary to convert RS232 interface to RS485 interface to obtain faster transmission speed and longer transmission distance as shown in Figures 17 & 18.

Figure 15: The internal circuit.

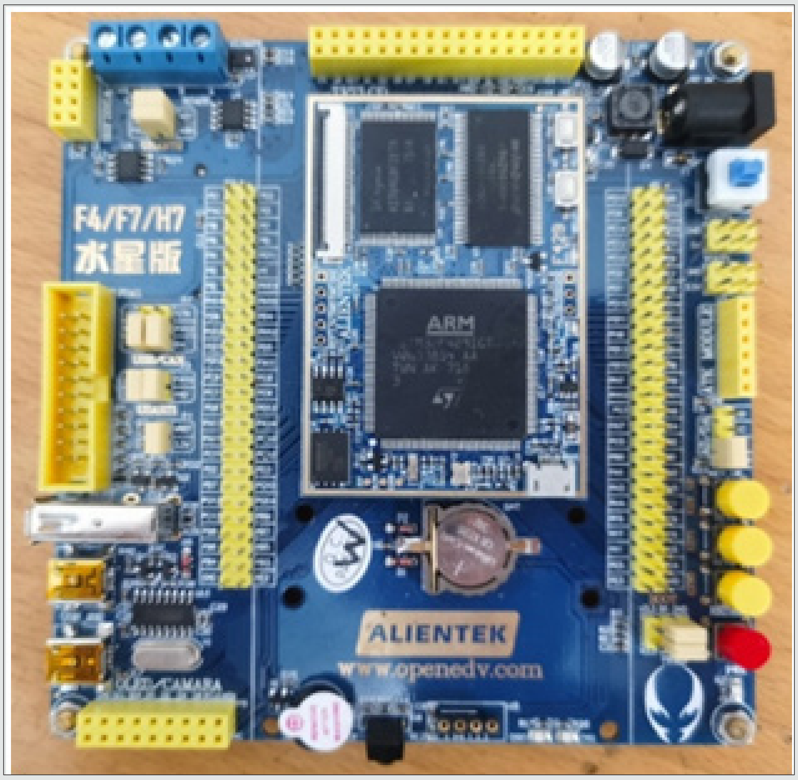

Figure 16: STM32F407 board.

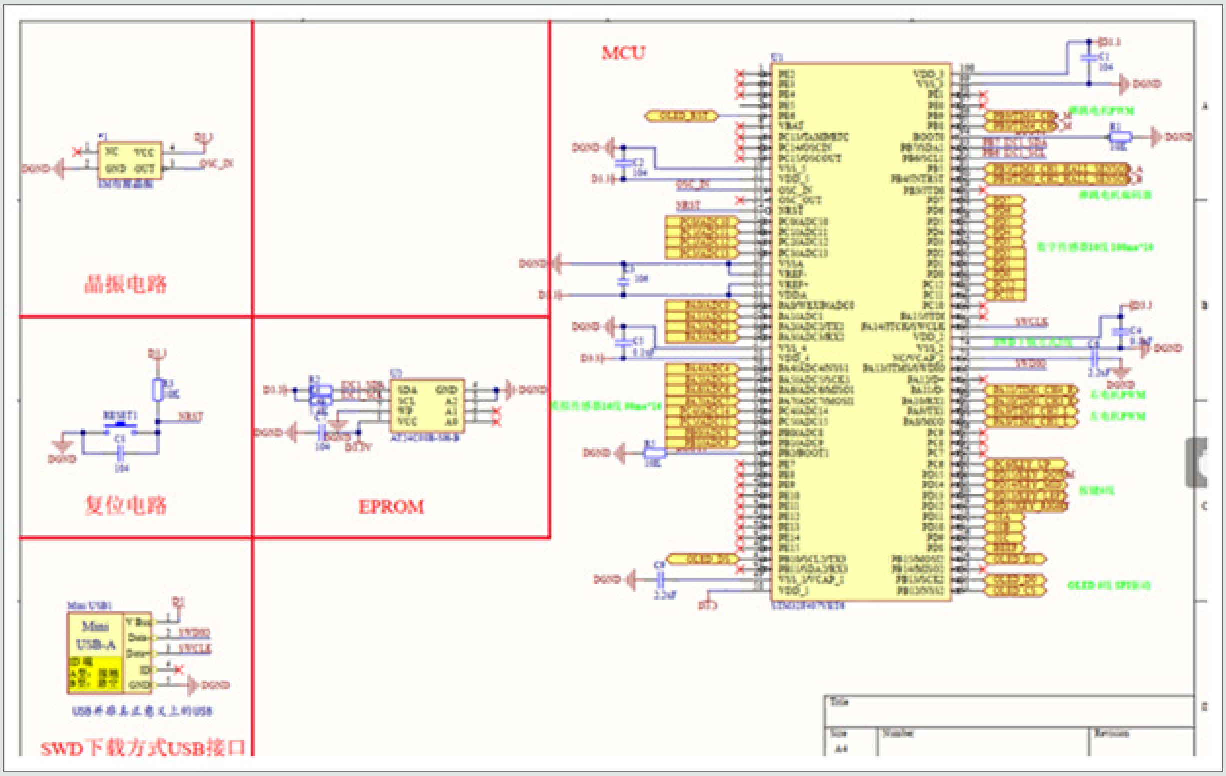

Figure 17: Part of the control circuit schematic.

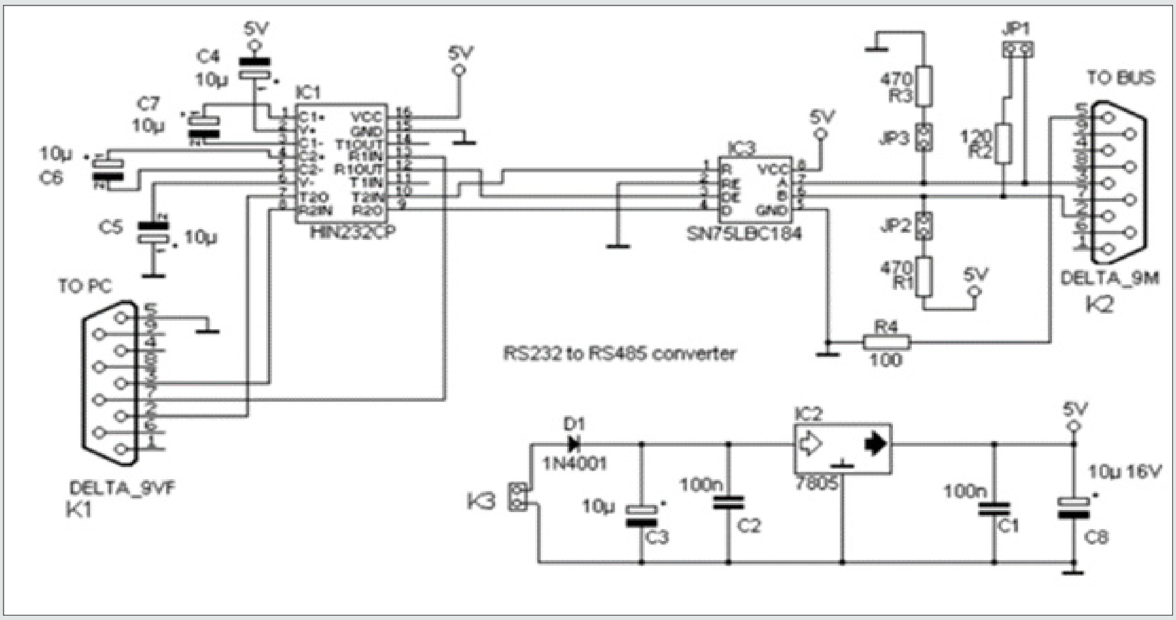

Figure 18: Transferring RS232 to RS485 circuit diagram.

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Remote control module

The STM32F407 chip used in the control system is a 32-bit processor with a total of 144 GPIO ports. These IO ports can be used as ordinary IO ports or multiplexed as serial ports. For example, the PA9 port and the PA10 port can be used as ordinary IO ports and can also be multiplexed as the sending and receiving pins of serial port 1. The chip has rich communication functions, such as IIC, SPI, RS232 serial port, RS485 serial port, etc. The underwater robot uses the NRF24L01 communication module, and SPI to communicate with the host computer STM32F407. The maximum data transmission speed can reach 10MHz, and the working state is stable and reliable. SPI is a full-duplex, synchronous communication bus that owns four lines to communicate with the controller, namely: (1) MISO, master data input, slave data output; (2) MOSI, master data output, slave data input; (3) SCLK, clock the signal is generated by the host; (4) CS, the slave chip select signal, is mainly controlled by the host. A brief diagram of the internal structure of SPI is shown in Figure 19.

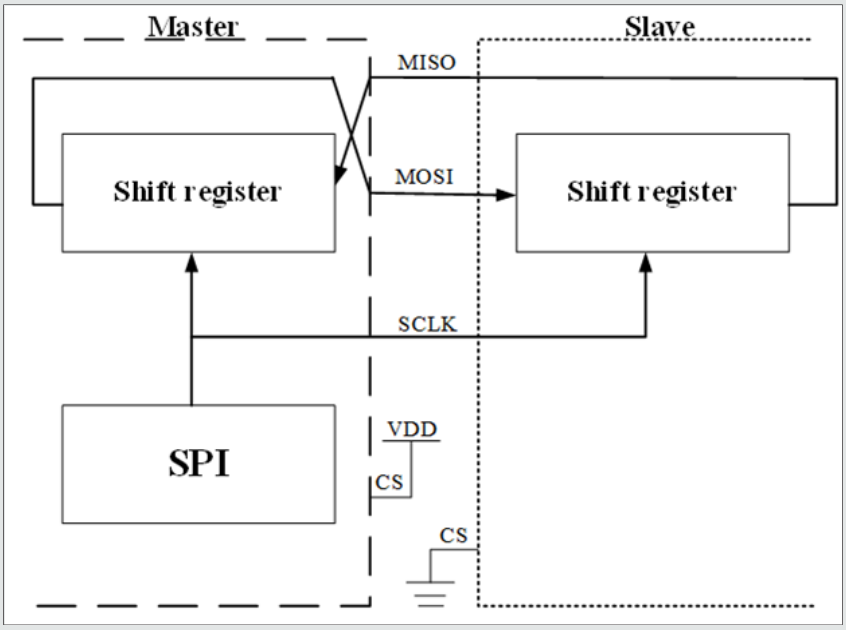

Figure 19: Graph of SPI.

As shown in Figure 19, from the hardware analysis, the SPI has only four lines in total. Both the master and the slave have a serial shift register. The SPI communication is full duplex. The data of the underwater robot and the remote-control box are transmitted at the same time. The transmission process is shown as follow. First, the control box sends a clock signal to confirm the underwater robot that communicates with the control box through the chip select signal line. The control box sends a byte: the control box sends the contents of the shift register to the underwater robot using the MOSI signal line. At the same time, the underwater robot also sends the data of the shift register to the control box using the MISO signal line. In this way, the data between the control box and the underwater robot is exchanged, so the control box manipulates the robot to move and work, and the robot also transmits images and information data inside the pressure vessel to the control terminal.

Inertial navigation module

The attitude sensor of the underwater robot adopts the JY-901 high-precision inertial navigation module, as shown in Figure 20 and Table 3. The inertial navigation module integrates high-precision gyroscopes, accelerometers and geomagnetic field sensors, with high-performance microprocessors, advanced dynamic calculation and digital filtering technology. It can effectively reduce the noise during work, with high accuracy and stability.

Table 3: Index meaning of inertial navigation module.

Index	Meaning
VCC	Inertial navigation module power
RX	Serial input
TX	Serial output
GND	Ground wire
SCL	I2C timeline
SDA	I2C data line
D0	Expansion port 0
D1	Expansion port 1
D2	Expansion port 2
D3	Expansion port 3

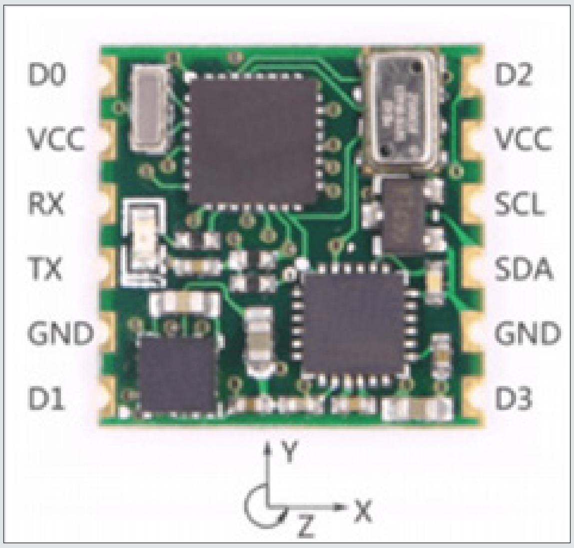

Figure 20: JY-901 high-precision inertial navigation module.

Depth measurement module

The depth solution system uses MS5837-30BA pressure sensor and is equipped with a depth solution board for depth solution work, as shown in Figure 21. As a new generation of high-resolution I2C interface pressure sensor, its measurement resolution is up to 2mm. It can work with all forms of microcontrollers, including the STM32F407 controller we use, and the communication protocol is very simple. The solver board and sensor will measure the pressure value of the environment, which is marked as the zero point of the depth output. The solution flow is shown in Figure 22.

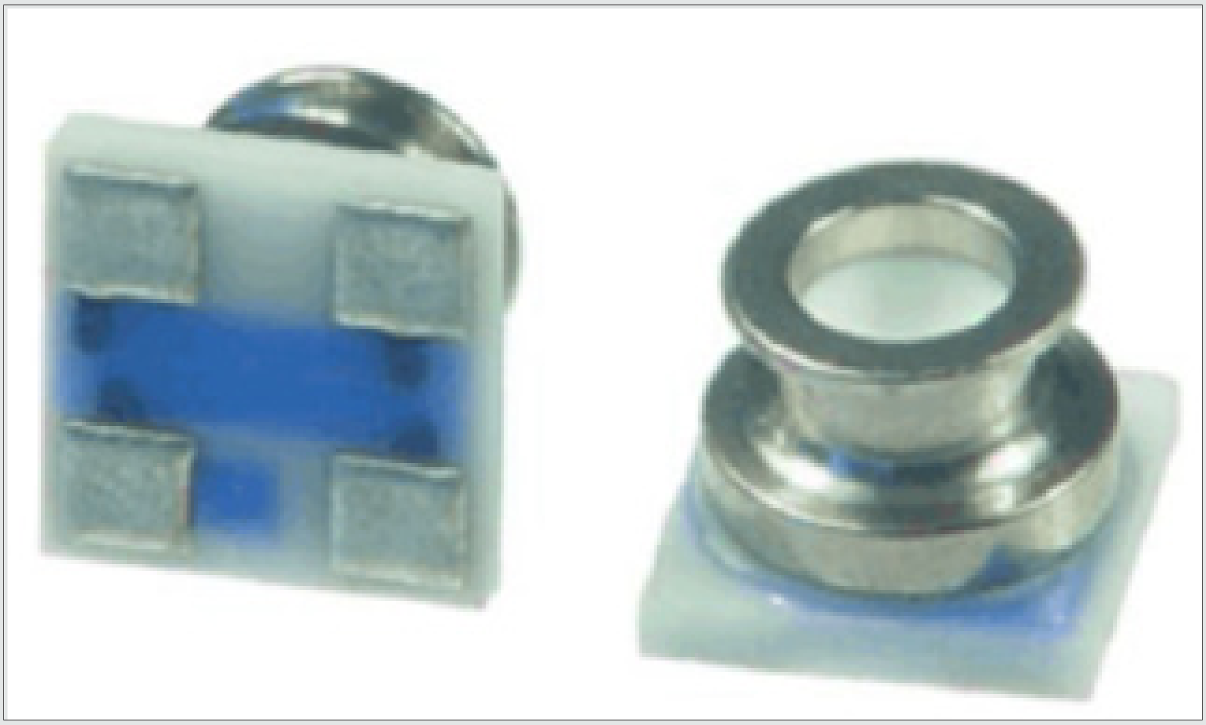

Figure 21: MS5837-30BA pressure sensor.

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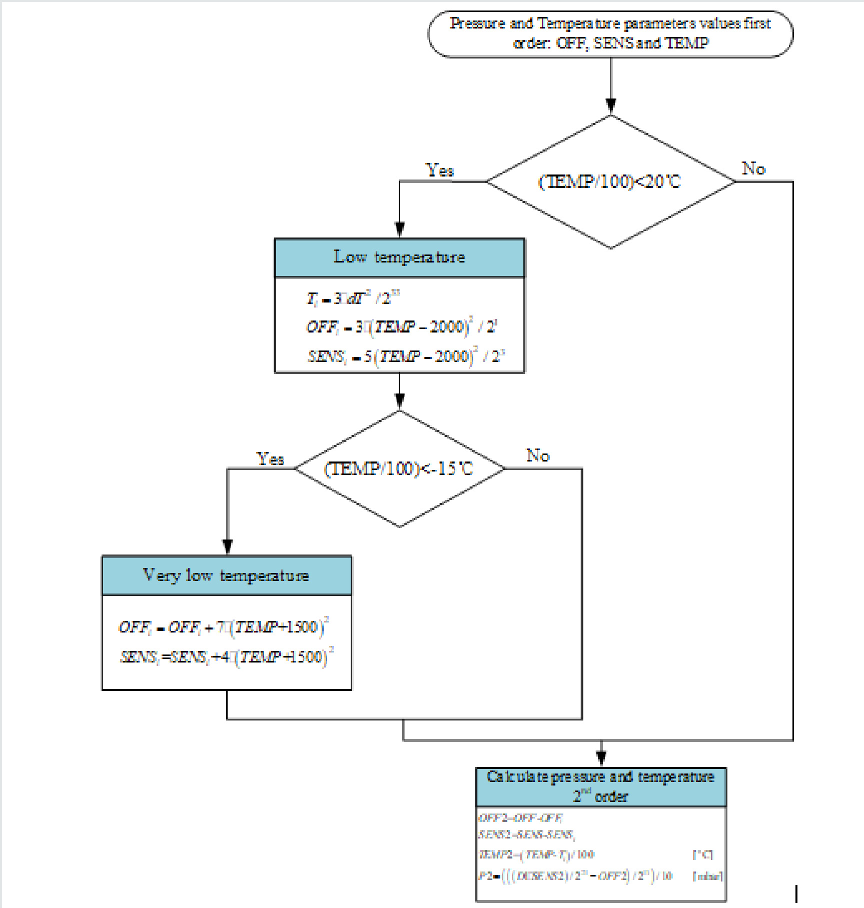


Figure 22: Solution flow for MS5837-30BA.

Experimental Verification of Underwater Robot Prototype

After the previous principal research and the overall design and modeling of the underwater robot, we carried out the production and debugging of the principle prototype and the pool experiment. In the pool experiment, the unit modules and working capabilities of the robot are fully tested to verify whether the design of the underwater robot can achieve the goal of this paper, that is, whether it can achieve the relevant cleaning work.

Fabrication and Assembly

The overall structure of the underwater robot is modeled, and 3D printed, as shown in Figure 23. The printed parts are placed in the order of assembly to facilitate the overall assembly, as shown in Figure 24. When the robot works underwater, it needs to carry electronic components such as core cabin and motor. Therefore, in addition to the electronic components that are uniformly arranged in the core cabin, the exposed motors, steering gears, propellers, etc. All electronic devices with special waterproof design, such as Waterproof steering gear, waterproof motor, underwater ESC, etc. At the same time, epoxy resin is used to encapsulate the joints of the 3D printed shell of the underwater robot, the connection between the shell and each module, and the inlay between the shell and the core cabin. Epoxy resin is a potting liquid glue with high permeability and high strength. During the potting process, the epoxy resin can be cured quickly without generating air bubbles, and it can also play a waterproof role. Based on the modeling and engineering drawings, we assemble and final pot the robot in order from bottom to top. The assembly process of the underwater robot is shown in Figure 25. Terminal control box and underwater robot prototype are expressed in Figure 26.

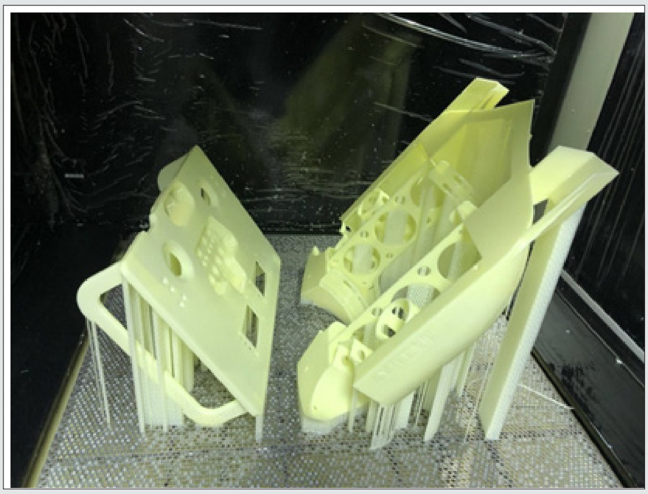


Figure 23: Underwater robot module parts being 3D printed.

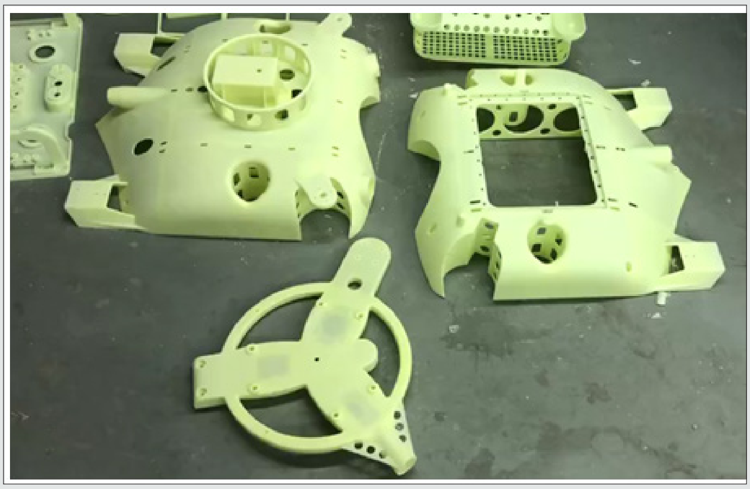


Figure 24: The underwater robot module parts after 3D printing is completed.

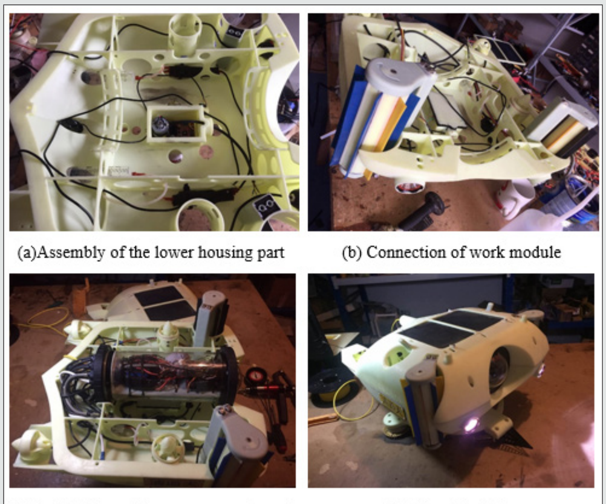


Figure 25: Underwater robot assembly process.

Figure 26: Terminal control box and underwater robot prototype.

System debugging

In order to prepare for further underwater test experiments, it is necessary to carry out overall inspection and debugging in the early stage. That is, mechanical structure assembly, electrical connection and debugging of functional modules. Firstly, adjusting the weight of the underwater robot. The adjustment of the weight is to adjust the force state of the robot to ensure that the robot will not roll over, tilt, sink, etc. Secondly, debugging of the robot's control system. The debugging of the control system mainly includes the debugging of the control chip and the joint debugging of the electronic circuits of various instruments and tools. The system debugging work mainly includes watertight connection and circuit testing. By testing the communication signal and output signal of each instrument individually, to ensure that the electronic circuit of each electronic device can work normally, as shown in Figure 27. Finally, the stress test. The core compartment houses most of the robot's electronic components. Therefore, in order to ensure the safety of the electronic components in the underwater robot control system, the waterproof and pressure-resistant test should be carried out on the pressure-resistant sealed shell containing the electronic components before the pool experiment. The design pressure-resistant water depth is 5 meters, so the pressure of the pressure-resistant chamber needs to be pumped to 149kpa and maintained for a period of time to confirm the experimental results, as shown in Figure 28. After the pressure and debugging experiment, the pressure resistance, tightness of the core cabin and the internal electronic components meet the required requirements, which means the pool experiment can be carried out on the robot.

Figure 27: System debugging of the robot.

Figure 28: Core cabin compression test.

Pool experiment

Figure 29: The experiment pool.

The pool experiment is to test the reliability of each module unit and overall function. The ultimate purpose of the pool experiment is to simulate the movement and work of the underwater robot inside the pressure vessel. Not considering the influence of wind and waves on the movement and work of the robot, this pool experiment is an indoor pool. The pool is 10 meters long, 5 meters wide, and the deepest point can reach 4.5 meters. The water conditions are very close to the internal environment of the pressure vessel, and it is suitable as an experimental site for underwater robots. The pool environment is shown in Figure 29. This pool experiment is mainly to test the functionality and stability of the underwater robot in the actual application environment, such as snorkeling ability, sports performance, working ability, image and data transmission and other content for further functional testing. The motion of the robot in the water is shown in Figure 30. Firstly, moving the robot on the surface and underwater, it can be obtained that its motion state is stable, and there are no situations such as heeling and rollover. Then, to complete the underwater work test of the cleaning disc and the robotic arm. Place debris at the bottom of the pool to simulate the bottom residue of the pressure vessel and pick it up by manipulating the robotic arm of the robot as shown in Figure 31. The second is to clean the debris stuck to the inner wall of the pool by manipulating the rotation of the grinding discs on both sides of the robot, so as to achieve the purpose of simulating the cleaning of the inner wall of the pressure vessel as shown in Figure 32. Data detection is carried out through its own camera module and various measuring instruments, as shown in the Figure 33. At this time, the voltage of the robot itself is 18.7V, the time is 18:57 in the evening, the ambient temperature is 27.3°C, and the water depth of the robot is 4.5m. Accurate image and data information transmission can be carried out through the photoelectric composite cable.

(a) state of motion on the surface (b) state of motion underwater

Figure 30: Motion of the robot in water.

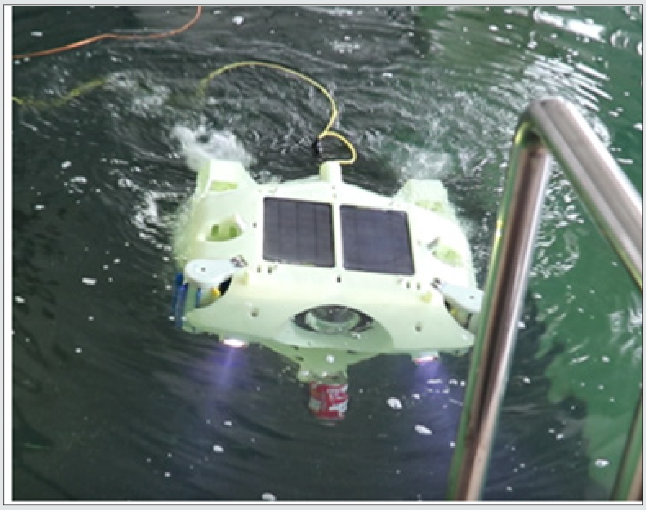


Figure 31: Grab underwater debris and return.

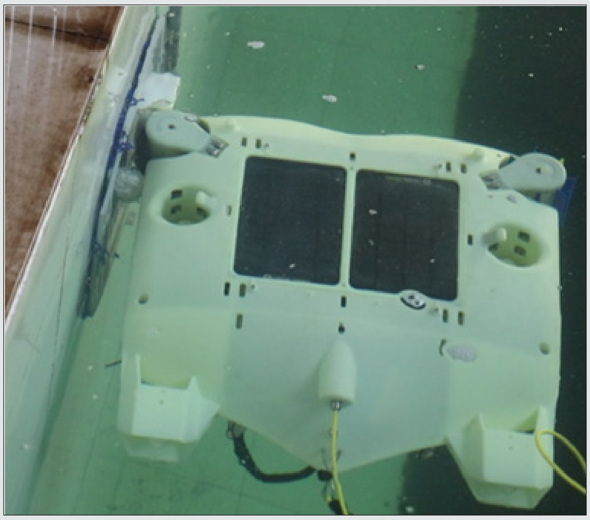
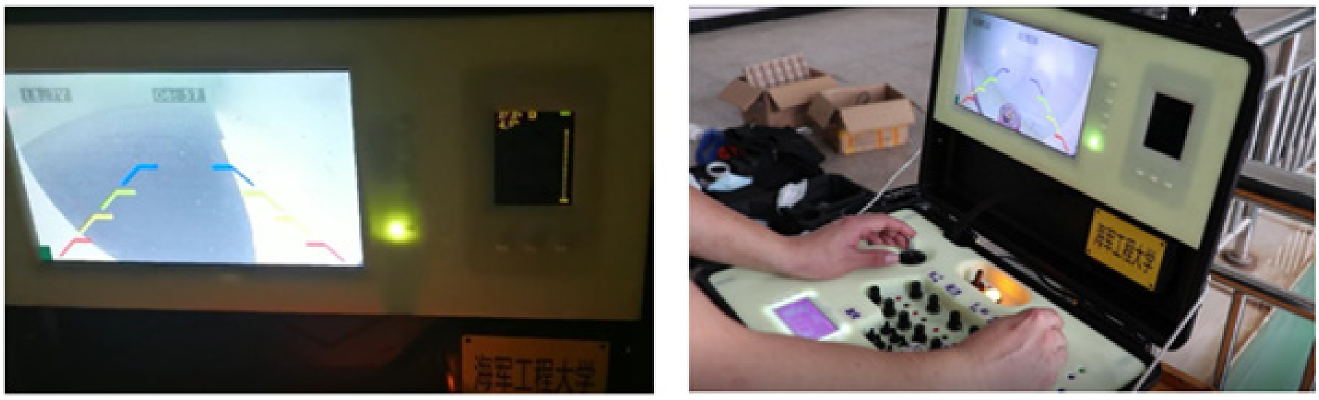


Figure 32: Clean the inside of the pool.



(a) Image and data display (b) manipulating the robotic arm

Figure 33: Control terminal display of the experimental process.

Conclusions and Future Work

The main thesis focuses on the tasks of cleaning and inspecting the inner surface of the pressure vessel and picking up the material dropped from the bottom during the process of mid-repair, refueling and decommissioning of the nuclear device. This paper designs and develops an underwater robot to complete radiation protection. Through investigation and analysis, the key technologies of the nuclear environment working robot are researched and discussed. And then, the structural design of the underwater robot is modeled by 3D using SolidWorks software, and the hardware of the robot is designed and applied. The summary of this topic mainly includes the following aspects:

a. The development and application status of radiation detection robots at home and abroad, providing reference cases for foreign robots used in radiation monitoring.

b. The body structure and the layout of each module of the underwater robot are systematically designed and arranged. A complete organizational structure is proposed, and a 3D model is established through SolidWorks software.

c. The pool experiment is carried out. The unit modules and overall functions of the robot have been fully tested at the same time. The test results showed the effectiveness of the underwater robot.

Meanwhile, the research's future work will focus on some aspects. Firstly, it is necessary to continuously adjust and optimize the function of the robot to clean the pressure vessel to meet the actual work needs. Secondly, to enhance the data measurement function of the underwater robot at work. The underwater robot can work stably in the radiation environment for a long time.

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