Design of structure and control system of an underwater vehicle for marine environment perception

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Abstract

With the increasingly severity of marine pollution and climate change, the protection of marine ecosystem is particularly important. In order to realize ship inspection, ocean cleanup and marine pollution detection, this work introduces an underwater vehicle for marine environment protection. An underwater vehicle for marine environment perception is comprised of land-based console, a zero buoyancy cable and an underwater vehicle motion platform. In particular, the video and sensor data collected by underwater vehicle system are displayed in real time through zero buoyancy cable back to the land-based console. This paper proposes a multi-stage PID cascade controller, aiming at the shortcomings of traditional proportional integral derivative (PID) algorithm. Underwater vehicle designed in this paper was tested in real environments such as ports and polluted sea areas, which were successfully completed.

Keywords: posture control, underwater vehicle system, marine environment perception

1. INTRODUCTION

Shipping is the main activity of the ocean. More than 80% of international trade goods are transported by freighter and cruise ships transport millions of tourists to their destinations. Every year, more than 50,000 ocean ships sail on the five oceans of the world, carry tens of billions of important commodities, including fuels, raw material and consumer goods [1, 2].

At the same time, the International Mathematical Organization (IMO) has established a legal and technical framework through its 172 member states, making shipping relatively sustainable [3]. Over the past ten years, the shipping industry implemented many measures such as new regulations and new forms of team training, aimed at improving shipping safety. Despite this change, transportation accidents especially collisions are still major problems. Recently, some statistical studies have identified human error as a major factor in most accidents at sea [4, 5]. Although innovations in marine technology and automation systems have contributed to improving shipping safety, but incidence rates of shipping accidents has increased and continued to have a negative impact on marine environment [4]. These accidents have a great impact in the marine environment, causing serious damage to the ecosystem.

An underwater vehicle is a device that can move through the water, it has a vision and perception system. It uses the manipulator remote control autonomous operation to assist people to complete certain tasks, such as underwater hull inspection, marine pollution detection and marine garbage cleaning. Application of marine environment perception underwater vehicle system and architecture are shown in figure 1.

Underwater vehicle is a challenging research field, whose expansion and replacement capabilities are valuable because they can be deployed in dangerous environments without endangering divers [6,7]. In general, underwater vehicles can be divided into two types: Remotely Operated Vehicle (ROV) and Autonomous Underwater Vehicle (AUV). ROV is a diving device that is controlled and monitored by operators. The vehicle receives signals and power from the land-based console through a cable. It is comprised of console, cable winch, power supply system and underwater equipment like thruster, repeater and vehicle body [8-13].

AUV is a diving device that has autonomous decision-making and control capabilities. The vehicle can realize autonomous decision making without real time operation. AUV can process the observed information, establish an environmental state model and transmit it to the land-based console [14-19]. With the console, operators can monitor the working process of the vehicle according to the environmental state model.

In this article, our vehicle uses NVIDIA JETSON TX2 as onboard computer because it is cheap and multi-processing capabilities. The onboard computer equipped with a GPU that can independently realize image processing functions. In addition, this paper designs a multi-stage PID controller, which can achieve precise depth control, allow more refined operations and capture better quality underwater images. Finally, we carry out the experiment, and the results show that the vehicle can overcome the complex underwater environment under challenging operational circumstances.

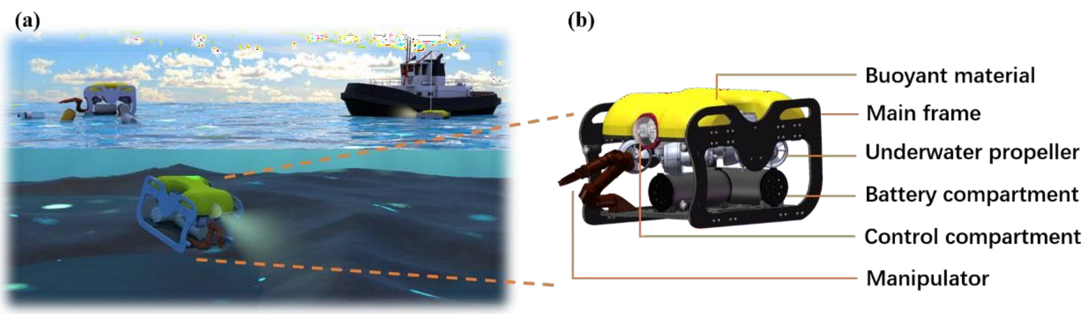

Figure 1. Application of marine environment perception underwater vehicle system and architecture. (a) Multiple application scenarios of marine environmental perception underwater vehicle systems; (b) Underwater vehicle architecture.

2. Technical parameters and sensors

This work introduces an underwater vehicle, for needs of underwater hull inspection, marine pollution detection and marine garbage cleaning tasks. The technical parameters of the final product are shown in Table 1.

Table 1. Technical parameters for underwater vehicle

Basic parameter		Forward thrust	14kgf
Length	457mm	Vertical thrust	9kgf
Height	338mm	Lateral thrust	14kgf
Net weight	9-10kg	**Cable indicators**	
Net buoyancy	0.2kg		
External diameter of seal cabin	110mm	Diameter	7.6mm
Floating body material	BR3318(200m) BF600（600m）	Length	25-30mm
Design index		Working strength	45kgf
Reachable depth	100m	Breaking strength	160kgf
Maximum speed	1m/s	Buoyancy	Positive buoyancy
Endurance time	2.5-3h	**Headlamp**	
Thruster	Single thruster of 5kgf	Luminance	1500 lumen water LED
Thruster configuration	Six thrusters	Degree of light beam	135 degrees

3. Structure design of underwater vehicle

The underwater vehicle is mainly comprised of three parts: land-based console, zero buoyancy floating cable and underwater vehicle motion platform.

3.1 Hull design

The underwater vehicle adopts a general open-shelf design, with control cabin, battery cabin, underwater thrusters and buoyancy materials. The open-shelf structure adopts High-density polyethylene（HDPE) mold to be pressed into plates, which are connected by 316 stainless steel connectors. Control cabin and battery cabin are arranged in the middle of the open-shelf structure. Both cabins are machined with aluminum alloy and anodized. The cabins are sealed with flanges, which opening at one end of the cabin used to install through bolts.

By analyzing the resistance characteristics of the open-shelf structure in underwater motion. We choose four horizontal thrusters with a thrust of 4kg are arranged in a parallelogram vector, the other two thrusters with a thrust of 6kg are placed in the vertical direction to realize floating and diving of the vehicle. The buoyancy material of underwater vehicle is made of hollow glass beads. By adjusting the number, size and position of buoyancy materials, the vehicle is made to have positive buoyancy.

3.2 Zero buoyancy cable design

Cable selection for the underwater observatory takes into account the need of release and communication. The cable will not only be able to communicate, but will also be able to pull underwater vehicle ashore in case of emergency. In the pool test, our vehicle was pulled back in still water at 1.4m/s, which required a pull of 12kgf. According to the above requirements this research contact the cable factory to customize the zero-buoyancy cable as shown in Figure 2.

The cable core is made of high-strength Kevlar fiber, with 4 pairs of twisted wires inside separated by polyester fiber and the outermost layer covered with polyethylene. The cable made of this fiber can maintain neutral buoyancy in sea water. The working strength of our cable is up to 35kgf and the breaking strength is up to 155kgf. One end of the cable is vulcanized and connected with a watertight connector to realize quick plug-in connection with underwater vehicle, the other end is connected to the cable to realize the release and recovery of the vehicle.

3.3 Land-based console design

The operation of underwater vehicle relies on land-based console for data processing and transmission. The land-based console adopts a computer architecture, including a motherboard, central processing unit, memory, hard disk, inverter, battery, power management circuit and display, which is convenient for operators to control and developers to carry out secondary development. The motherboard, central processing unit, memory and hard disk form a computer system, after installing the Linux operating system and underwater vehicle control program, operators can easily realize underwater vehicle's attitude control and sensor data collection. The battery and power management circuit transmit power to the components of land-based console, which uses 18650mAh rechargeable lithium batteries. At the same time, the inverter mounted on land-based console is used to output 220V 50Hz alternating current to supply power to display.

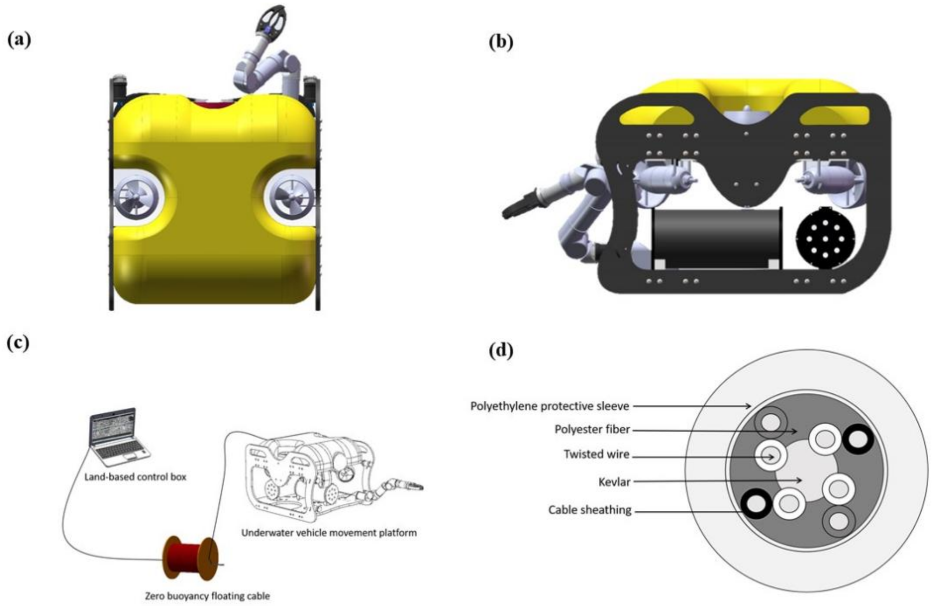

Figure 2. Underwater intelligent robot system architecture. (a) Top view of the underwater vehicle body motion platform; (b) Side view of the underwater vehicle body motion platform; (c) General framework of underwater intelligent vehicle system; (d) Zero buoyancy cable structure

4. Control system design

Design diagram of underwater vehicle control system is shown in Figure 3. The system is sealed in control cabin and its core modules are self-designed main control board and NAVIDIA JETSON TX2 embedded artificial intelligence computing device. The main control board processor is STM32F407 microcontroller, which contains ARM Cortex M4 kernel and main frequency 168MHz. It has the advantages of fast calculation speed and strong real-time performance.

Main control board integrates two independent Inertial Measurement Unit (IMU) systems. One adopts ICM-20602 6-axis motion tracking device, which combines a 3-axis gyroscope with a 3-axis accelerometer and uses an AK8975 3-axis magnetometer as an electronic compass. The other adopts a MPU6050 6-axis Micro Electro Mechanical System (MEMS) motion tracking device, which includes a gyroscope and an accelerometer. An IST8310 three-axis digital magnetometer is used as an electronic compass. This combined design greatly improves the stability of underwater vehicle control system. In addition, the main control board also integrates a micro-USB interface, an Analog to Digital (A/D) module, 2 serial ports and 8 Pulse Width Modulation (PWM) output interfaces.

The vehicle calculates its real-time attitude and depth information by IMU system and transmits it to the main control board by serial port interface. The STM32F407 encapsulates the above status information through the (Micro Air Vehicle Link) MAVLINK protocol and sends it to Jetson TX2 through the Micro-USB interface. At the same time, the Jetson TX2 receives control commands from the land-based console and transmits them to the main control board. After receiving the command, the board combines it with the vehicle attitude information, calculates the thrusters output in real time by using the motion control algorithm and drives the thrusters through the Electronic Speed Control (ESC) system at the PWM output port.

When underwater vehicle is working, it is necessary to monitor its safety status. Therefore, a water leakage sensor has been added to each sealed cabin. When sensors detect water leakage into one sealed cabin, vehicle invoke vertical thrusters to float above the surface of the ocean.

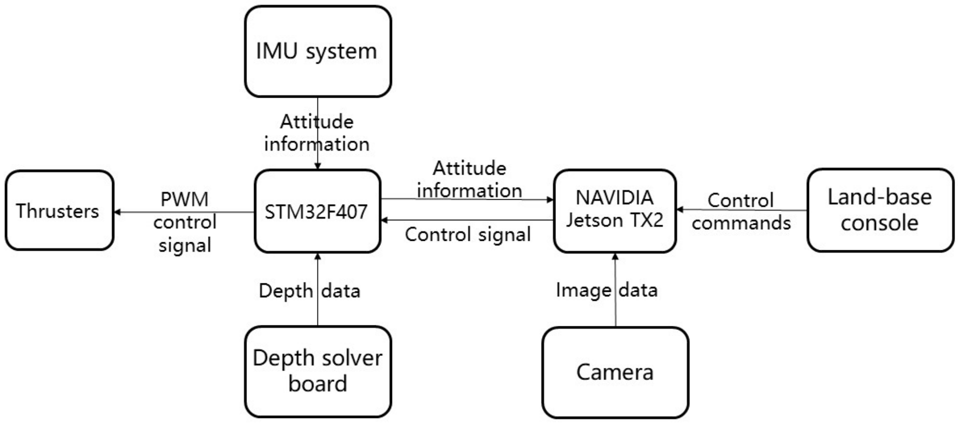

Figure 3. Underwater vehicle control system design block diagram

5. Control algorithm

5.1 Attitude and inertial navigation algorithm

The realization of the stable control of underwater vehicle is inseparable from the accurate perception of its own attitude. In this paper, the Butterworth filter and the moving average filter are used specifically to remove high-frequency noise in data collected by various sensors. The main control board reads these data and executes navigation algorithm to convert it into its own attitude information. The Attitude and inertial navigation algorithms, which can convert the filtered sensor data into real-time attitude angle, depth, velocity and acceleration information of underwater vehicle.

5.2 Heading control algorithm

In this paper, we designed a multi-stage PID algorithm, the heading control is divided into inner and outer loop multi-stage control, the structure diagram is shown in Figure 4. When land console does not send new control commands, our vehicle uses heading angular velocity and angle multi-stage control algorithm to maintain the heading angle.

In the angle loop control, expected angle is always set to 0 degrees to lock the heading angle of the underwater vehicle. The heading angle obtained by solution algorithm is used as the feedback of angle loop controller, aim to calculate the desired angular velocity of it. The angular velocity loop controller uses desired angular velocity and heading angular velocity calculated by the solution system for closed-loop control of angular velocity. At the output end, a hybrid controller distributes the output to four horizontal thrusters to realize the lock of heading angle of the underwater vehicle.

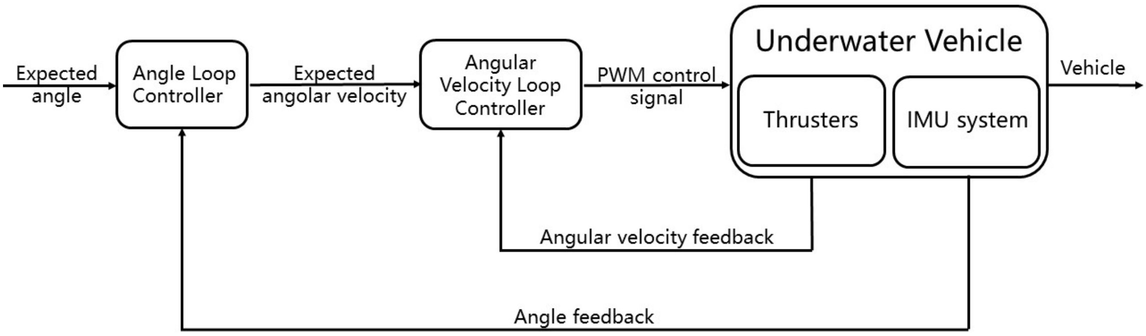

Figure 4. Structure of multi-stage angular PID controller

When the land console sends a heading control command to the underwater vehicle, the controller is switched from multi-stage PID controller to single-stage angular velocity PID controller. The structure diagram of the single-stage angular velocity controller is shown in Figure 5.

The operator sends a desired heading angular velocity to underwater vehicle through land console, then PID controller uses the heading angular velocity, which calculated by the controller as a feedback value. In the end, the controller use heading angular velocity feedback value and desired heading angular velocity to obtain the value of attitude error, as a result to perform real-time closed-loop control of the heading angular velocity to achieve the desired control effect.

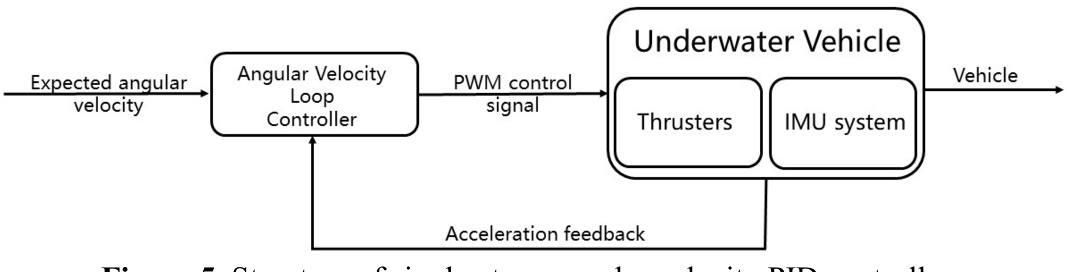

Figure 5. Structure of single-stage angular velocity PID controller

5.3 Depth Control Algorithm

There are difficulties in the depth control of underwater vehicles. Underwater thrusters have a certain hysteresis, there will be oscillation phenomenon during the depth control. In addition, the interference of ocean currents brings a lot of uncertainty to the control of vehicles in the real environment.

There are many studies on the depth control of underwater vehicles in the world, such as depth control method of underwater vehicle based on fuzzy control [20], terminal synovial controller was used to realize automatic depth determination control of ROV [21], uses PD control algorithm to realize ROV depth control [22]. The key to the performance of PD controller lies in the setting of PD parameters. Facing the complicated marine environment, simple PID control can no longer meet the needs of actual engineering. Aim at the shortcomings of traditional control algorithms, this paper proposes a PID multi-stage controller to achieve better depth control effects. The controller framework is shown in Figure 6.

Similar to the heading control, the depth control of underwater vehicle is also divided into two situations. One is when the operator does not send depth control commands, the vehicle realize the fixed depth control. The other is when operator sends depth control commands, at which time the vehicle obtains a desired speed of ascent or descent.

Underwater vehicle depth control is divided into three levels of PID multi-stage control. Depth loop PID controller based on the inertial navigation system, use the depth of underwater vehicle to calculate its expected speed and use the speed and its current speed to calculate the velocity error value. Then use speed loop controller for the vertical speed and calculate the expectation of underwater vehicle acceleration value. Finally, the error value of acceleration is calculated and the closed-loop control is carried out. The three-stage PID controller can be used to control the depth of the underwater vehicle well and can effectively resist the interference of the marine environment to achieve stable operation.

After sending the depth control commands to the vehicle from the land console, the vehicle will switch to speed control in the vertical direction. At this time, the depth loop controller will be abandoned and the velocity sent by land console will be taken as expected velocity of the vehicle. The closed-loop control of velocity and acceleration will be carried out to achieve the desired motion effect.

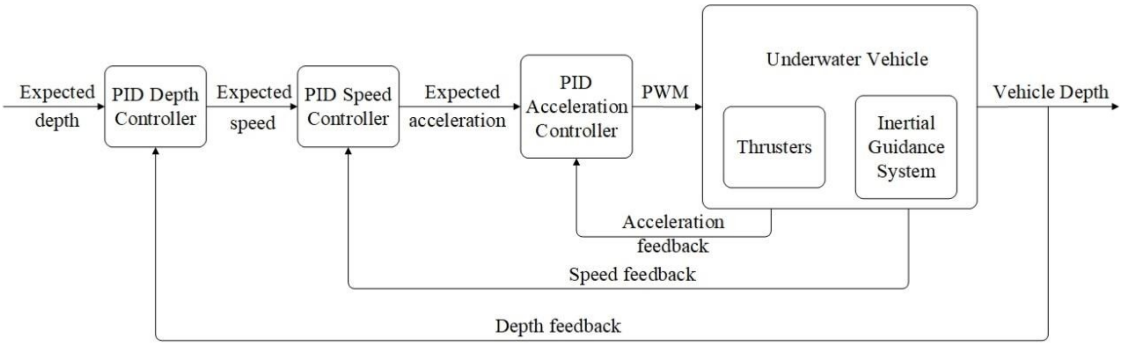

Figure 6. Structure of depth loop PID controller

6. Experiment

The underwater vehicle made in this paper is put into the real environment for testing. The hull inspection mainly involves three aspects: the underwater part of the hull, the main propeller and the lateral propeller. The underwater parts of the hull include the two sides under the draft, the bottom planks, rudder and rudder fins, the bottom door, the drain, the bilge keel, the half guide hood and the zinc on the outside planks. Inspection of main propeller, including propeller wing, propeller hub and propeller hub cap. The inspection of the side propeller is mainly to check its condition. The hull inspection needs to observe whether the parts involved in these three inspection aspects have peeled off the coating surface, rusted, stained and marine biological attachment. If there is any need to take photos and report the specific location, quantity and area.

During the test, the underwater vehicle first launched from the bow of the ship, turned around along the bilge keel of the hull, observed the condition of the hull and recorded the image. Then divide the captain into three equal parts, select three points from one side of the ship and cross across the other side of the ship. Figure 7 is the inspection of the training ship of Dalian Maritime University. Through the test, the body and control algorithm of the underwater robot designed in this paper can withstand the test of the ocean environment, run stably in the ocean and successfully complete the hull inspection task and obtain clear underwater images of different depths.

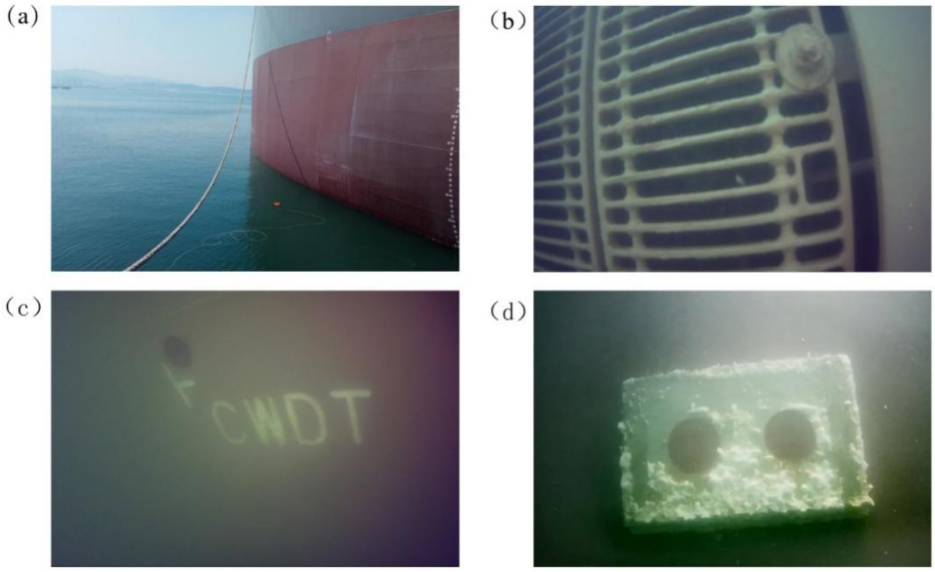

Figure 7. (a) At the time of testing, (b) Check the submarine gate, (c) Inspection of the hull surface, (d) Zinc block on rudder surface was detected

7. Conclusion

This paper describes the design of structure and control algorithm of underwater vehicle for ship safety, marine garbage collection and marine environment monitoring. This is a compact, high-performance underwater vehicle. The submergence depth index of the vehicle is 100 meters and it can work flexibly in this range.

At the same time, a multi-stage PID multi-stage controller is designed. It ensures that the underwater vehicle can run stably and achieve the function of fixed navigation and depth, so it can capture high-quality underwater images. The real environment test proves that the designed underwater vehicle can work reliably in the ocean environment. The vehicle body and control algorithm designed in this paper lay a foundation for the realization of automatic cruise monitoring of underwater vehicle in the future, which has valuable commercial and military value.

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