A Variable Buoyancy System and a Recovery System Developed for a Deep-sea AUV Qianlong Ⅰ

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Abstract—**As a new generation of deep-sea Autonomous Underwater Vehicle (AUV), Qianlong Ⅰ is a 6000m rated glass deep-sea manganese nodules detection AUV which based on the CR01 and the CR02 deep-sea AUVs and developed by Shenyang Institute of Automation, the Chinese Academy of Sciences from 2010. The Qianlong Ⅰ was tested in the thousand-isles lake in Zhejiang Province of China during November 2012 to March 2013 and the sea trials were conducted in the South China Sea during April 20-May 2, 2013 after the lake tests and the ocean application completed in October 2013. This paper describes two key problems encountered in the process of developing Qianlong Ⅰ, including the launch and recovery systems development and variable buoyancy system development. Results from the recent lake and sea trails are presented, and future missions and development plans are discussed.**

Keywords—Deep-sea AUV; Qianlong Ⅰ; Launch and Recovery Systems (LRS); Variable Buoyancy System (VBS).

I. INTRODUCTION

Deep-sea Autonomous Underwater Vehicle (AUV) is a complex underwater work platform[1]which many countries now either operational or in advanced stages of development. For example, the WHOI's ABE AUV has been operational mainly for the accurate terrain mapping and seafloor hydrothermal vents investigation more than ten years. The 4500m leveled SENTRY AUV has the more maneuverability advantage and is replacing the tasks of ABE [2-3]; REMUS 6000 is the maximum depth AUV of REMUS series developed by MBARI, which has the capability of seafloor terrain mapping [4,5]. BLUEFIN-21 is also an AUV designed for deep-sea exploration [6]. AutoSub6000 is a 6000m rated glass AUV which is well placed to become one of the world's most capable deep diving AUVs and it have emphasized the "Auto" part of its name [7] .These underwater vehicles have important significance in deep-sea resource exploration and military applications and the missions all beyond 3000m deep.

"Qianlong Ⅰ" was developed on the basis of "CR01" and "CR02"which the development targets and difficulties focus more on the convenience of the practical applications compared to the previous two generations deep-sea AUVs. There are some problems exists in the previous two generations AUVs: (1) Recovering process requires an auxiliary boat, which the process is not only hard to operating but also has threaten to staff's safety on the boat; (2) Owing to the deep depth, the hydrological parameters vary greatly in the diving process. These parameters can cause continuous buoyancy variation during the AUV diving. There need several times diving for balancing due to the buoyancy variation not very clearly for the first two generations of AUVs. (3) The long voyage navigation accuracy is low which results the low accuracy of detection.

Aiming at the existed problems of the two generations AUVs, we firmly committed to solve these issues from the early stage of development. This paper describes how we are dealing with these issues at the design level, reports on the results the trials process of "Qianlong Ⅰ" on launch and recovery systems and the variable buoyancy system. According to the several issues above, we explains the solutions to solve these problems, reports the concrete results of "Qianlong Ⅰ" lake and sea experiments and applications, also looks towards the future development idea and the major work.

II. BACKGROUND

Qianlong Ⅰ AUV is mainly used for deep-sea manganese nodules detection in 6000m rated glass deep ocean, it also has capacity of seabed topography and bottom profile measurement, seabed photography, hydrological parameters measurement et al . "Qianlong Ⅰ" also has the obstacle avoidance ability in the complex underwater environment. It has broad application prospects in marine mineral resources exploration and marine biological resources exploration. The main specifications of the "Qianlong Ⅰ" shown in Table 1.

TABLE I. SPECIFICATION OF QIANLONG Ⅰ

Serial	Specification	index
1	Depth	6000m
2	Endurance	24hours
3	Dimensions	ϕ0.8m × 5m
4	Weight in air	1500kg

The endurance index of Qianlong Ⅰ requires that its sailing time is not less than 24 hours with the speed of 2 knots, but it can be reached more than 30 hours through the lake test. On both sides of the vehicle install sensors including side scan sonar, underwater cameras, CTD, dissolved oxygen, turbidity, EH, PH. The sensors layout of Qianlong Ⅰ is shown in

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Figure1. The AUV has underwater acoustic communications capability and long baseline navigation positioning function.

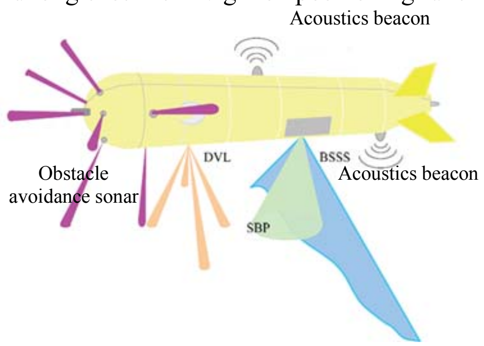


Fig.1 The sensor layout of the Qianlong Ⅰ

Qianlong Ⅰ AUV is mainly equipped on the Ocean VI scientific surveying ship. The primary lifting equipment of Ocean VI is an A-frame located on stern of the deck. The Ocean VI with the low speed navigation control ability and the dynamic positioning capability. The maximum height from lifting points of A-frame to deck of Ocean VI is 6.5m and the maximum distance of the lifting points extends the stern is 7m. The A-frame of Ocean VI with 16 tons dynamic lifting capacity. Its height from recovery deck to sea level is about 2.7 meters and a cable winch equipped on the deck.

Adopting the unpowered ways to diving and floating, the Qianlong Ⅰ relies on loading diving ballast and expelling floating ballast to achieve fast spiral diving and floating

III. Development and Methods

A. Mechanical design

Adopting with modular design methods, Qianlong Ⅰ is divided into 12 modules in total. The head of Qianlong Ⅰ is hemisphere with the radius of 397.8mm and it with a cylinder body with the diameter of 795.6mm, the ending is a streamlined body with the length of 1200mm. Tail stabilizer fins of Qianlong Ⅰ also maintains its original state of X-type as CR01 and CR02 and the airfoil profile is NACA0006, the wing area is 13.4×10-4m2. The main thruster is mounted between the stabilizer fins with "+" character and the propellers does not extends circular cross-section constituted with stabilizer fins. On the back of the vehicle set two rings which are used for vehicle's launch and recovery operations, the distance between two rings is 2.2m.

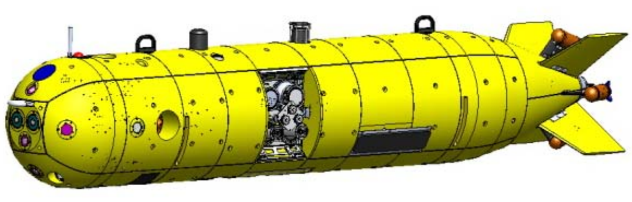
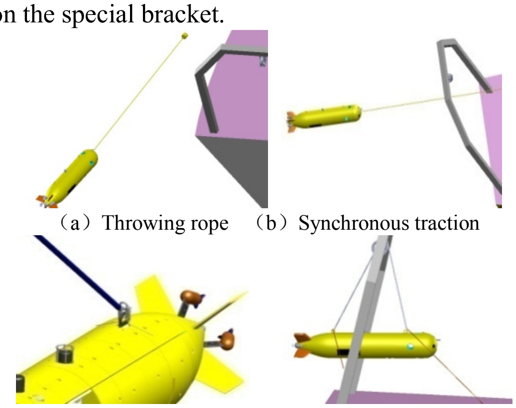


Fig.2 "Qianlong Ⅰ" AUV

B. Recovery System

It is always a key issue of the project that development a recovery system for Qianlong Ⅰ. The main development objectives of the launch and recovery systems of Qianlong Ⅰ are include: 1. To complete operations without additional reconstructed utilize existing available assemblies wherever possible especially the A-frame of the "Ocean VI". 2. Can operate in up to sea-state 4 without small boat assistance.3. In addition, the launch and recovery system should be simple to reduce the cost and have the adaptability for the other ships.

The overall recovery operation procedures of Qianlong Ⅰ are shown in Figure 3. When the AUV completes the detection mission, it floats to the sea surface by throws away the ballast. Then the AUV transmits its position to the surface vessel via radio, the surface vessel sails near to the AUV after receives the position messages. The projectile head and rope be throw out of the AUV through remote-control when the vessel at about 50 meters away from the AUV, shown in Figure 3a. The surface vessel continues closes to the AUV according to parallel with the rope, then the staffs salvage the rope through the rope-capture device. The rope will be transferred in the A-frame which is assembled on the stern of the surface vessel. Then slowly pulled the traction rope back through the winch assembled on the deck and make the AUV sail parallel and synchronized with the vessel which sails against current slowly, shown in figure 3b. Then gradually tighten the rope until the AUV below the A–frame and to connect the lifting belt with the rings of the AUV use lifting lock, shown in Figure3c. After operations mentioned above finished, then sling the AUV from the water under the auspices of swing-ended cable, shown in Figure3d. Finally, the AUV is completely sling onto the deck of the vessel and fixed on the special bracket.



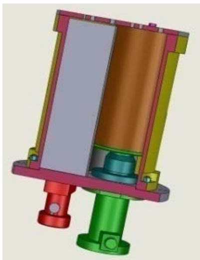
（a）Throwing rope （b）Synchronous traction

（c）Padlock （d）Lifting

Fig.3 The recovery process of Qianlong Ⅰ

The launch and recovery system was synchronized developed with Qianlong Ⅰ AUV. There are two key devices involves in the recovery system including rope throwing device and recovery lifting locks. The rope throwing device is installed on the vehicle head which the main function is thrown the projectile head and traction ropes from the vehicle shown in Figure 4. The pyrotechnic driver components of the rope-throwing device working principle is that exploding force of gunpowder makes projectiles flying out of the device together with traction rope. The main composition material of the projectile head is syntactic foam used for buoyancy, and the rope's density is less than seawater, therefore projectile head and rope can float in the sea surface.

The lifting lock and its lever are the other key composition recovery device which is used to connect the lifting belt to the ring of the AUV's, shown as Figure5. The lifting belts and the lifting rings on the AUV can be connected through the lifting locks by using the carbon fiber rod while the AUV is towed sailing synchronous with the surface vessel. Pulling the carbon fiber rod back hard when the lifting rings were locked by the lifting locks credibly, the breakable item will be destroyed so that the carbon fiber rod separate from the lifting lock. The lifting lock can be separated from the lifting ring through pulling a manual open plate of the lifting lock after the AUV recovered.



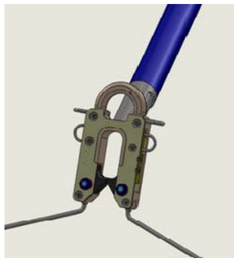


Fig.4 Rope throwing device   Fig.5 Lifting lock and carbon fiber rod

C. Buoyancy Change and Regulation

1. Buoyancy Change

The temperature, pressure and salinity change greatly in the process of diving which cause the buoyancy changing constantly in the process of diving and greatly affect the vehicle's underwater sailing performance. The AUV buoyancy variation during the diving is mainly due to the buoyancy variation caused by the seawater density change and AUV water displacement change. The most fundamental reason is that the bulk coefficient between water and AUV is inconsistent with the variation of pressure and temperature. The water density variation includes temperature, depth and salinity, while the AUV water displacement depends primarily on the depth and temperature change during the diving. Therefore the main factors of the buoyancy variation in the process of diving include temperature, salinity and depth.

2. Variable Buoyancy System

The buoyancy adjustment has unidirectional characteristic of Qianlong Ⅰ in the diving process. In this article, a unidirectional variable buoyancy system was designed shown in Figure 6. The system uses hydraulic oil as working medium and is mounted outside the "Qianlong Ⅰ" when diving in unfamiliar waters at the first diving. Through adjustment buoyancy using variable buoyancy system, we can achieve optimal working buoyancy state at the required diving depth just need one time diving and could also carry out exploration mission at the same time. It improves the economic benefit and convenience of 6,000m AUV greatly that with variable buoyancy system.

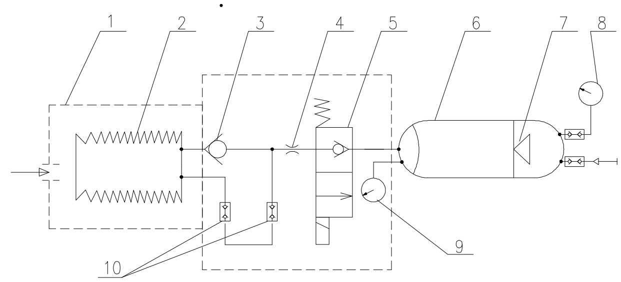
Fig.6 The variable buoyancy system was installed on Qianlong Ⅰ

The hydraulic principle of variable buoyancy system of Qianlong Ⅰ shown in Figure 7. When the vehicle needs to reduce the buoyancy under a certain depth, the oil in external bladder was flow into the internal bladder by opening the normally closed solenoid valve and the oil driven by the external water pressure.

After the oil flows into the internal bladder which in a pressure hull, the gas volume inside the hull is compressed that induced the pressure increases in the hull, while the total quality of the inside pressure hull is constant, so through measuring the pressure and the temperature inside the pressure hull, we can calculate the oil volume in the external bladder according to the gas compression law, as the equation in (1)

$$V = V_0 - \frac{P_0 V_0 T}{T_0 P} \quad (1)$$

Where, V is the oil volume in the external bladder; V_0 is the initial volume of pressure hull; P_0 is the initial pressure of the pressure hull; T_0 is the initial temperature; P is the measured pressure of gas ; T is the gas temperature inside the pressure hull, because the value is not easy to measure, so we replace it with ambient temperature. In this variable buoyancy system, $V_0 = 7.5L$ and the volume of external oil bladder is $6L$.



1 - external leakage shell 2 - external bladder 3 - check valve 4 - throttling element 5 - normally closed solenoid valve 6 - pressure hull 7 - internal gas 8 - inflatable gauge 9 - internal pressure gauge 10 - oil-filled connectors

Fig.7 System hydraulic principles

IV. THE RESULTS OF LAKE AND SEA TRIALS

A. Lake trails

The lake trails of Qianlong Ⅰ carried out in November 2012 - March 2013 in Zhejiang Province, China. The control parameters meets the navigational requirements and through adjusting the controlling parameters equipped the variable buoyancy system with Qianlong Ⅰ.In order to do the integrated buoyancy adjustment test on the lake condition, the initial positive buoyancy of the vehicle was adjusted to 91N. The ultimate aim of vehicle is to achieve optimal buoyancy regulation sailing of 25N. The maximum buoyancy regulating amount of variable buoyancy system is 120N. The lake trail shows that the regulation accuracy of variable buoyancy system is 6N and this accuracy meets the engineering requirements entirely. The buoyancy variable has little effect on the vehicle’s center of gravity, the pitch angle and roll angle of the vehicle is almost the same. The economy and convenience of the Qianlong Ⅰ greatly increased with this system in unknown waters.

B. Sea trails

Qianlong Ⅰ AUV carried out the sea trails on April 20, 2013 - May 2 in the South China Sea. The depth of the sea is approximately 4200m. In this experiment, seven times of launch and recovery operations altogether were carried out. The recovery process was shown in Figure12. The sea conditions of most tests were generally calm but one time sea state 3 during the final test. The launch and recovery operations can be successfully conducted without the small boat assistance and it takes an average of 30 minutes from the rope was throw to the AUV was assembled on the "Ocean VI" deck. The launch and recovery system has been further applied in the subsequent Qianlong Ⅰ AUV's ocean application in October 2013 and another seven launch and recovery sorties were accomplished under the state once up to 4. In the ocean application, the water depth is approximately 5200m, and the actual maximum diving depth is 5080m.

Fig.8 recovery process of the vehicle

Unfortunately, due to the arrangements of the sea trial is very urgent and to avoid security risk, there is no arrangement for variable buoyancy system deep-sea trail. However, during the sea trail we measured the hydrological parameters of the sea area and balancing the AUV through gradually added lead. In the Through trails, we know that Qianlong increasing additional about 119.6N positive buoyancy in 4,100m depth compared to the sea surface in 40m. And the buoyancy is increasing about 140N at 5080m depth in the experimental ocean application in October 2013.

V. CONCLUSIONS AND FUTURE WORK

The Qianlong Ⅰ AUV has great improvement on navigation precision and endurance compared to CR01 and CR02. In particular, the launch and recovery system and variable buoyancy systems are firstly applied that the first two generations vehicles have not these functions.

The low cost launch and recovery system for a large deep-sea AUV Qianlong Ⅰ was developed which can be used in variety of readily available vessels. A series of trials for launch and recovery operations were done on the lake and the sea during the period of November 2012 to October 2013.During the period of sea trials, 14 times launch and recovery sorties were conducted in all under sea conduction is generally calm but two times approached sea state 3 and 1 times close to sea state 4.

A single direction variable buoyancy system was developed for Qianlong First to reduce the diving times and improve the quality of balancing. By the buoyancy adjusting, the balancing optimum is carried into effect at the first time diving and can be carried out the detection task in the same diving. There is no need to diving for balancing in the unknown waters in the course of deep sea detection because of the variable buoyancy system.

On the basis of the above trail experiences, a new concept put forward to develop a new generation 6000m level underwater vehicle which is focus on making the usage more convenient and user-friendliness. A new generation of vehicle is expected to adopt more comprehensive modular design.

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