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Review on underwater docking technology of AUV

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Abstract: Autonomous Underwater Vehicles (AUV) form an important link between water surface support platforms, submarine stations and deep sea long-term observation systems. The underwater docking technology of AUVs has long been a research hotspot at home and abroad. In the induction and analysis of AUV underwater docking technology at home and abroad, such as underwater box (cage) docking, robot or carrier-assisted docking, pole guidance docking, platform blocking cable docking and bell-mouth guidance docking, the implementation methods and structural principles of various AUV docking technologies at home and abroad are introduced, as well as the development status and development trends of docking technology. In light of the widely used bell-mouth guidance docking method, a submerged docking system for heavy-duty AUVs is introduced in detail. The experiment proves that this system has strong modularity and low requirements for roll attitude. It is suitable for AUVs of various sizes, and the docking success rate of the docking system is high. The findings of this study can provide useful references for the future development of AUV underwater docking technology.

Key words: Autonomous Underwater Vehicles (AUV); underwater docking; structural principle; bell-mouth guidance docking; review

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0 Introduction

With the continuous development of technology, underwater vehicles have become one of the important tools for marine development. Due to its good maneuverability and capability of cruising in a wide range of sea state, autonomous underwater vehicles (AUVs) play an important role in underwater observation, mapping, positioning and deep sea sampling[1]. However, due to the little progress of battery technology in recent years, limited energy reserves of AUV itself and high power consumption in using instrument, when the energy is about to be exhausted, AUV needs to return to the mother ship to replenish battery in time, which makes the range of underwater operation is greatly limited, thus increasing the cost of using AUV[2]. The launch and recovery of AUV require both the support of the mother ship and a lot of manpower and material resources, and also pose certain risks. In order to improve the efficiency and operation range of AUV, to meet the needs of collection and transmission of oceanographic information, marine exploration and special operations, it is necessary to study the underwater docking technology of AUV. Underwater docking technology of AUV is the key to energy replenishment and underwater data uploading and task downloading for AUV, and is essential for building 3D oceanographic observing systems[3]. At present, many countries have funded to actively develop the underwater docking technology of AUV. However, due to the different shapes and sizes of various type of AUVs, their underwater docking meth-

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ods are different.

1 AUV underwater docking technology available

In the past three decades, researchers worldwide designed and developed a variety of AUV underwater docking systems, which have their own characteristics, based on different docking bodies and docking environments. At present, the countries that have funded to research underwater docking technologies abroad mainly include the US, Japan, Norway, Sweden, the UK and Italy. In China, the notable organizations for underwater docking technology research mainly are the Shenyang Institute of Automation Chinese Academy of Sciences, Zhejiang University, Harbin Engineering University and China Ship Scientific Research Center. The five groups of available underwater docking systems that have developed until now are summarized as follows: underwater box (cage) docking, robot or carrier-assisted docking, pole guidance docking, platform blocking cable docking and bell-mouth guidance docking [4]. This article aims to present introduction of these underwater docking technologies respectively.

1.1 Underwater box (cage) docking

The underwater box (cage) docking is an early AUV docking recovery method. This method not only requires the support of the mother ship and the recovery device, but also requires a large number of personnel to participate, which is seriously affected by the waves. For this kind of docking method, the most representative is the "Explorer" underwater docking recovery system designed by Shenyang Institute of Automation Chinese Academy of Sciences.

In 1994, Shenyang Institute of Automation Chinese Academy of Sciences developed underwater box (cage) docking recovery system [5] for the "Explorer", as shown in Fig. 1. The system consists of two parts: the above water part includes the control console and lifting equipment, and the underwater part includes the repeater and a large underwater recovery body [6-7]. The recovery body is used to complete the docking and release with the AUVs, and is mainly composed of a frame, a U-shaped frame, a buoyancy retractable manipulator, a driven retractable manipulator, a hydraulic system, a propeller, a sensor and an underwater camera. The relative position of the AUV and the recovery body is observed by the underwater camera. When the AUV moves to the proper position on the recovery body, it falls into the recovery device, and then the hydraulic system drives the buoyancy manipulator to lock the AUV. Finally, the U-shaped frame is stowed, in this way, the docking of the AUV and the recovery device is completed [8-9]. This method requires the AUV to accurately locate and recover the docking device during the recovery process, and constantly adjust its own motion attitude. Since the on-board operator observes the position of the AUV through the screen of the camera to determine the time of locking the AUV, the positioning accuracy of the method is not high.

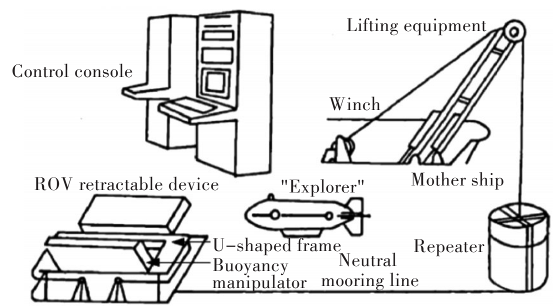

Fig.1 "Explorer" underwater docking recovery system

1.2 Robot or carrier-assisted docking

The robot or carrier-assisted docking is an autonomous docking recovery system applied to military submarines, mainly including robotic docking recovery and AUV auxiliary docking recovery. The robotic docking recovery is assisted by the robot to achieve the docking. The AUV auxiliary docking recovery is assisted by the carrier such as the remotely operated vehicles (ROVs) to recover the AUV with typical ones being the LMRS (long-term mine reconnaissance system) AUV underwater docking recovery system[10] and Swedish "Sea Hawk" ROV auxiliary docking recovery system.

The LMRS AUV underwater recovery system, funded by the US Navy's LMRS project, uses the submarine's 533 mm torpedo tube to launch and recover the AUV, as shown in Fig. 2, which is verified in the USS Hartford nuclear powered submarine in 2007. This recovery system is an option dedicated to military application. The LMRS AUV (the length is 5.88 m, and diameter is 510 mm) launched by torpedo tube of submarine will adjust its speed and attitude when receiving the recovery command from the submarine, and then autonomously operated into the submarine's torpedo tube. The submarine is equipped with upper and lower torpedo tubes, and robot is equipped in the upper torpedo tube, which can extend outward, and capture, clamp and position AUV during the docking process [11]. The capture process is roughly as follows. After the robot has extended the full length, the front joint of the robot is hydraulically driven to bend down a certain angle, then the AUV approaches from the stern of the submarine to the bow while extending its own mooring mast and inserting it into the mooring cone hole of the robot and fixing it through the cooperation of AUV' motion. Finally, the AUV moves into the torpedo tube under the guidance of the Manipulator arm [12]. The recovery process of this kind of docking method is complicated for it is not completely autonomous, which requires very high precision on control and is difficult to capture AUV in case of the great influence of current.

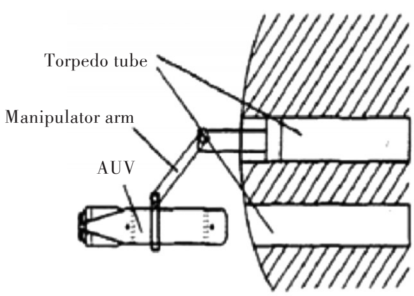

Fig.2 LMRS AUV underwater recovery system

Fig. 3 shows the "Sea Hawk" ROV auxiliary docking recovery system. The recovery process of the system is roughly as follows. When they are docking, the "Sea Hawk" ROV is released firstly in the torpedo tube of submarine, and then the on-board operator controls the ROV to keep approaching the AUV62F through the video taken by the ROV and the returned sonar image. When the ROV moves close enough to AUV62F, it will capture the AUV62F by the loop carried by it and tighten the fixed loop at the predetermined position (because there is a suction cup at the bottom of the "Sea Hawk" ROV, it will catch up the AUV62F). Finally, the on-board operator controls the "Sea Hawk" ROV to drag the AUV62F into the torpedo tube to complete the recovery [12].

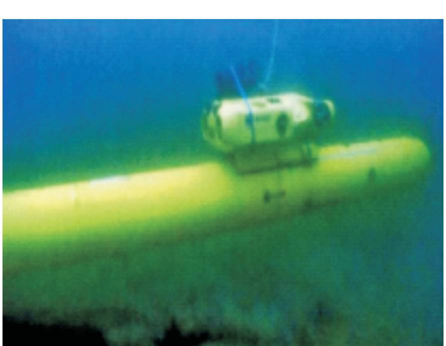

Fig.3 "Sea Hawk" ROV auxiliary docking recovery system

1.3 Pole guidance docking

This docking method is achieved by the cooperation of the capture mechanism on the AUV and the catcher on the docking mechanism. For this type of docking, the representative is the Odyssey IIB AUV underwater docking system in the US. The system is jointly developed by MIT and the Woods Hole Oceanographic Institute (WHOI) in 2001. It mainly consists of a V-shaped shear, a positioning pole, a locking mechanism and a pedestal [13], as shown in Fig. 4.

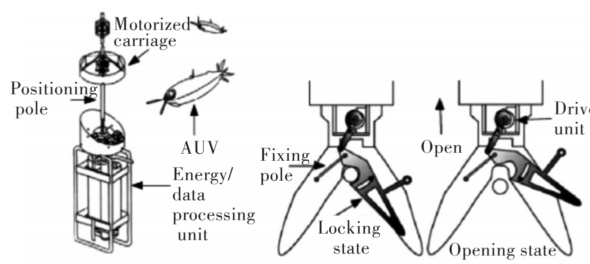

Fig.4 Odyssey IIB AUV underwater docking system

The Odyssey IIB underwater docking system is a kind of pole guidance docking that provides energy replenishment, data exchange and fault detection for the AUV. The system realizes docking through a V-shaped shear structure on the AUV, a positioning pole on the docking pedestal and a sliding cover at the upper end of the pole. When the AUV is close to the docking mechanism, the V-shaped shear triggers spring on the AUV, and then the catcher will be positioned to the side by the positioning pole. The positioning pole enters the groove of the "V-shaped shear" and is locked by the catcher, while the sliding cover on upper end falls and locks the AUV. Moreover, the drive unit should pull the catcher to release the positioning pole when it needs to be opened [14]. The docking method has the advantages of all-round docking, the requirement for the positioning accuracy of the AUV is not very high, the interference by the marine environment is relatively small, and the reliability of the docking is high, which largely ensures the success rate of the docking. However, the docking method requires a V-shaped guiding mechanism at the front end of the AUV, which affects the motion performance of the AUV and increases the energy consumption of it. In addition, the positioning and locking unit of the docking device is also complicated [15].

1.4 Platform blocking cable docking

The method of the platform blocking cable docking is similar to the landing of an aircraft to the aircraft carrier. When docking is required, the AUV is slowly descending towards the underwater base in seabed, and finally the recovery is realized both by the locking mechanism on the base and the AUV. For this type of underwater docking system, representative is the Marine-bird system [16], developed by Kawasaki shipbuilding corporation of Japan, as shown in Fig. 5.

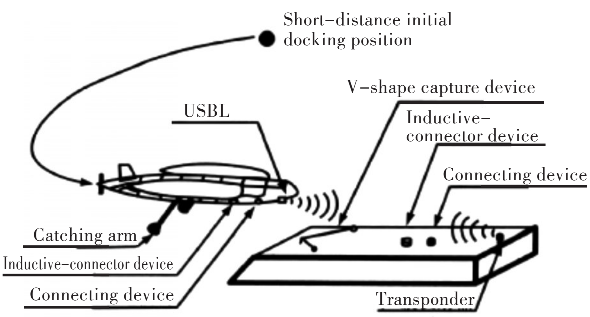

Fig.5 Marine-bird underwater docking system

The Marine-bird system is a kind of platform blocking cable docking. In 2003, Kawasaki corporation completed the docking system of the AUV and the platform through experiments. The docking system relies on ultrashort baseline (USBL) array to guide the AUV to return. When the AUV approach to the base, the base sends a signal to guide the AUV to slowly descend, and then the V-shaped capture device (guide for catching) on the base hooks the catching arm released by AUV to achieve positioning and AUV is locked by connecting device. Both the AUV's catching arm and the capture device on the base are in a V-shaped arrangement, and the two are spatially interlaced. After the catching arm comes into contact with the capture device, the AUV's motion space is getting smaller and smaller, and finally the AUV is completely positioned [17]. After docking, the AUV and the platform rely on the induction coil for charging. The docking method is suitable for the docking process of the underwater base, the success rate and positioning accuracy are relatively low, and the requirements for AUV self-pilot and power system are relatively high.

1.5 Bell-mouth guidance docking

The bell-mouth guidance docking is relatively simple in structure, and the docking device adopts a guide housing or a cage structure, which does not need to greatly modify the AUV, and has a certain protection effect on the AUV after docking, but the AUV is required to have very good motion control and maneuverability. This docking system is more susceptible to the hydrodynamic interaction between the docking mechanism and the ocean current [18]. Since the access port has an open structure, the AUV can be guided to enter the docking device in the correct posture, so that the AUV is allowed to have a certain deviation when approaching the docking structure, which largely ensures the success rate of the docking. For the bell-mouth guidance docking, the representative ones are Remus underwater docking system, Bluefin underwater docking system, AUV underwater docking system developed by Harbin Engineering University and China Ship Scientific Research Center, and AUV underwater docking system "Dolphin II" of Zhejiang University, etc.

The Remus underwater docking system (as shown in Fig. 6) is developed by the WHOI with energy replenishment and data exchange capabilities for the AUV. The docking system is simple in structure and can be parked on the seabed, pulled by the relay communication buoys to sink in the water, or towed by the mother ship [18]. The structure uses a combination of a tapered guide housing and a cylindrical underwater docking station (UDS) to guide and position the AUV [19]. An USBL array is arranged above the tapered guide housing for positioning and navigation of the AUV during the docking process. The USBL module is distributed in the fore body of the AUV, and the guiding distance of docking is 3 000 m with the resolution being less than 0.5° [20-21]. The system uses a linear actuator to guide the watertight electrical connector to be plugged and unplugged for charging and data transmission. The charging unit consists of a pair of guiding pins and a charging connector, and the connection is realized by that the linear driving structure drives the guiding pin to be inserted into the guiding hole on the AUV, and the guiding pin will limit the relative motion of the AUV to the docking device. Multiple sea trials by the US military have demonstrated that the Remus AUV can accurately enter a tapered guide housing with a diameter of only 80 cm from a few nautical miles away under the guidance of an USBL array, with a success rate of single docking of 60% [22-23]. This docking method does not require major changes to the AUV, but requires high positioning accuracy and ability of motion control. Fig. 7 shows the Remus underwater docking process.

Bluefin underwater docking system adopts bell-mouth type guided docking. The overall structure is similar to the Remus docking device. The docking system and the docking structure are shown

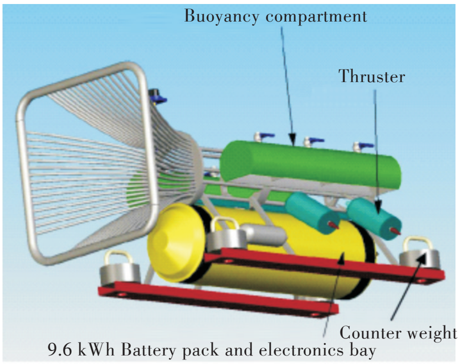

Fig.6 Remus underwater docking system

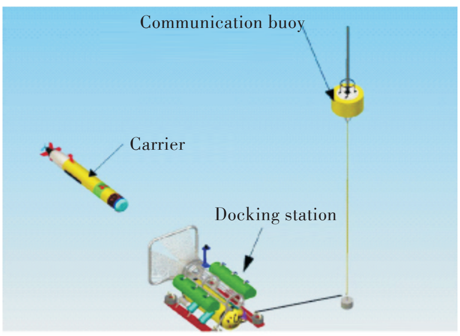

Fig.7 Remus underwater docking process

in Fig. 8 and Fig. 9, respectively.

The AUV underwater docking system jointly developed by Harbin Engineering University and China Ship Scientific Research Center uses the bell-mouth guidance docking. The docking system and the carrier used for docking are shown in Fig. 10 and Fig. 11, respectively. Furthermore, the docking system is successfully tested in October 2015. Since the entrance size of the docking mechanism is relatively small, it is necessary to achieve docking by means of high-precision altitude measurement technology, navigation technology, self-planning and motion control technology. In order to obtain the precise position of the AUV for the entrance of docking mechanism, the team of Harbin Engineering University develops an USBL navigation and positioning technology system to achieve accurate ranging and positioning through the transponder installed at the entrance of the docking mechanism and the USBL array on the AUV. With the underwater acoustic guidance and positioning system and inertial navigation system carried by AUV, through self-planning & decision-making and intelligent motion control, the posture of AUV is constantly self-aligned to the entrance of the platform before entering the docking mechanism. In this way, it can smoothly enter the docking mechanism with trumpet shape for wireless information transmission and underwater wireless charging. After entering the docking mechanism, the mechanism uses the lifting lugs on the AUV to enter the guide plates on the docking mechanism to limit the roll and position. By placing two V-shaped blocks directly below the AUV, the V-shaped block is driven to clamp the AUV between the docking frame and the V-shaped block to complete the AUV locking.

Fig.8 Bluefin underwater docking system

Fig.10 AUV underwater docking system

Fig.9 Bluefin underwater docking structure

Fig.11 Carrier for underwater docking

Zhejiang University has developed the "Dolphin II" on the basis of the AUV "Exploration 100" of the Shenyang Institute of Automation Chinese Academy of Sciences, which has completed its own autonomous docking test in the South China Sea in May 2017. In the sea area at depth of up to 50 m, the AUV and the non-contact underwater docking system of seabed observation network carries out 11 autonomous docking operations, and 10 of them are successful. The underwater docking mechanism uses a bell-mouth guidance docking, as shown in Fig. 12. The bell-mouth structure has an inlet diameter of 1.1 m and 60° cone angle [24]. The docking system uses electromagnetic locking technology to achieve fixing of AUV, while using wireless charging and non-contact data transmission [25].

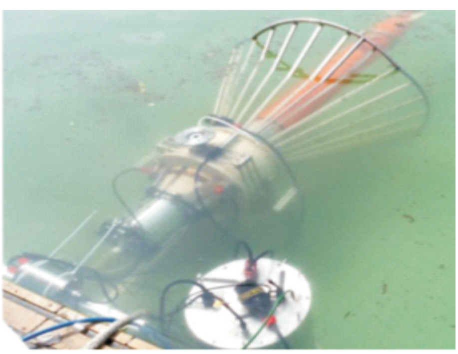

Fig.12 "Dolphin II" AUV underwater docking system

The above-mentioned typical AUV underwater docking methods have different structures with their own characteristics.

1) The early developed underwater box (cage) docking method have low positioning accuracy and docking accuracy, low technical difficulty, high efficiency, flexible method and high reliability and safety. However, the docking recovery system is complex and is subject to sea states and weather, which are not conducive to covert deployment.

2) Robot or carrier-assisted docking is suitable for the docking of AUV on submarine. The docking method is more complicated and specific. It has high requirements for AUV´s motion control capability, and its recovery process is not completely autonomous with high requirement of accuracy for control.

3) Although the pole guidance docking has low requirements on the motion accuracy of the AUV and can achieve 360° docking, but it needs to add a structure similar to the V-shaped shear to the AUV, which has an influence on the motion performance of the AUV, and the docking system has a complicated structure.

4) The positioning accuracy of the platform blocking cable docking is high, the requirements for self-pilot and power system of AUV are high, and the docking success rate and positioning accuracy are not as good as the pole guidance docking and the bell-mouth guidance docking.

5) For the bell-mouth guidance docking, firstly, there is no need to modify or change the AUV, which has little effect on the motion performance of the AUV. Secondly, because the bell-mouth guidance docking adopts the open structure, even the AUV and the axes of the docking mechanism do not coincide (the deviation is within a certain range), the AUV can also be docked under the guidance of the open structure. This type of docking system can not only reduce the requirements for end-guide, but also provide a more reliable locking device and protective housing, as well as more convenient and reliable charging and transmission of data[26]. The bell-mouth guidance docking has higher practicability and reliability than other types, and is a widely used AUV underwater docking system.

2 Research on heavy-duty AUV underwater docking system

In view of the advantages and disadvantages of the above various docking methods, the Shenyang Institute of Automation Chinese Academy of Sciences has designed a bell-mouth guidance underwater docking system for heavy-duty AUVs, as shown in Fig. 13.

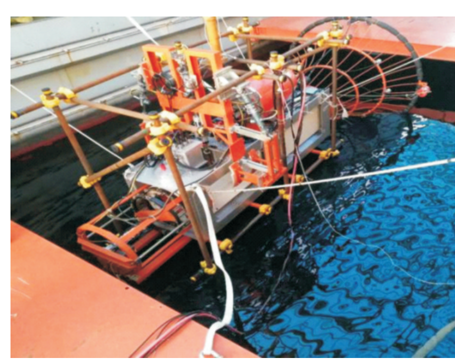

Fig.13 Heavy AUV underwater docking system

In December 2017, the Shenyang Institute of Automation Chinese Academy of Sciences conducted a test on the key technologies of the AUV underwater docking at the Qiandaohu lake test site. The trial carried out 10 strips, each of which had 3 docking opportunities and successfully completed all 10 dockings.

During the docking process, the AUV relying on the navigational positioning information provided by the inertial navigation system and the USBL underwater acoustic guidance and positioning system navigates to the set target of the hovering position, and then solves the position of the docking device and adjusts its own motion attitude. After the solution of the target position is completed, the AUV performs depth-keeping navigation, and the center depth of the cross-section must be consistent with the center depth of the docking device, so that it can smoothly enter the interior of the docking device and perform underwater wired high-power charging.

The underwater docking process of the AUV is an autonomously guided process, as shown in Fig. 14, which uses the USBL acoustic positioning method to locate the AUV and the docking device. The presence of water flow and noise will have great impact on the accuracy of underwater docking. Therefore, the device adopts a bell-mouth guide housing to guide the AUV into the docking device, which largely guarantees the success rate of the docking. At the same time, a transponder is evenly arranged on the guide housing for receiving the sonar signal of the AUV, thereby calculating the position and attitude of the AUV, and realizing the positioning between the AUV and the docking device. AUV relies on inertial navigation system and underwater acoustic guidance and positioning system to continuously search and track the docking mechanism and adjust its own motion attitude through autonomous decision-making and planned intelligent motion control. Furthermore, it will adjust to the position of the entrance before docking, thus ensuring the AUV smoothly enter the docking mechanism.

When AUV slowly enters the docking device, in order to protect the sonar device in the fore body of the AUV, a protective plate is installed on the inner

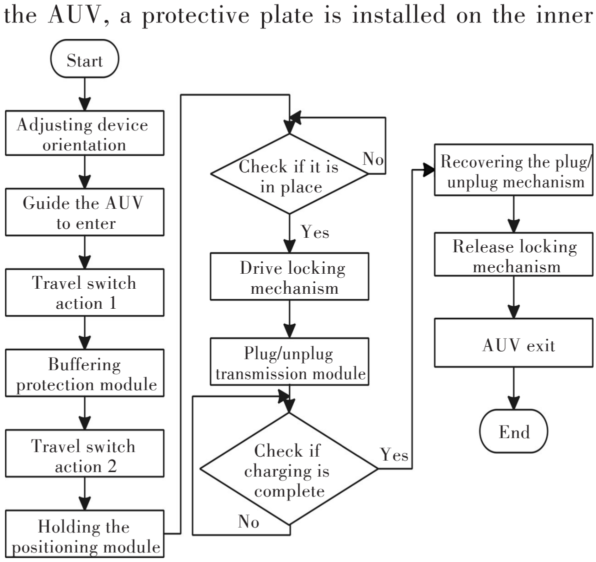

Fig.14 AUV underwater docking process

wall of docking device to serve as a buffer. The AUV enters the docking mechanism via the guide housing. After AUV main thruster stops working, the AUV is pushed back to the designated position by the propulsion device on docking platform. Due to the limited movement range of the underwater charging and data transmission plug/unplug device the AUV needs to be axially positioned. Namely, the docking guiding device is designed behind the bell mouth, and the guiding device adopts an overall cylindrical structure. After the AUV contacts the overhead guard of fore body, the AUV main thruster is closed, then the full stroke is pushed by a hydraulic cylinder with a maximum stroke of 200 mm, and the AUV is pushed back to the designated position for axial positioning.

After the AUV enters the docking mechanism, in order to align positioning of the AUV, the horizontal direction is positioned by the propulsion mechanism, and the vertical direction is positioned by the locking mechanism. The alignment is achieved by the positioning pin and the triangular groove on the sides of AUV. To decrease the impact of water flow on the stability of AUV after docking, a symmetrical limit clamping device is designed on the docking mechanism, which mainly relies on the hydraulic cylinder to drive the linkage mechanism.

After the AUV is stably docked, the plug/unplug device starts to function, charging and transmitting data to AUV. Considering the error exist when docking, a universal joint is installed on the plug/unplug assembly, so that the plug can have a certain degree of swing in plugging/unplugging operation, thereby achieving flexible docking. The hydraulic cylinder drives plug to be connected to connector socket on the AUV carrier, so as to complete the connection and supply energy and transfer information to AUV.

3 Conclusions

The AUV underwater docking technology plays an important role in the construction of submarine stations and deep sea long-term observation networks. It is an important guarantee for offering AUVs to operate underwater for extended duration. With the deepening of research, the docking technology will be more diversified, such as the dynamic docking of AUV and USV, the dynamic docking of AUV and docking mechanism, etc. This will greatly help to form the underwater Internet of Things (IoT). Underwater docking technology will help us better understand the ocean and have great application value in both civil and military fields.

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一种基于人工势场多AUV集群的实时避障方法

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摘 要：[**目的**] 针对复杂水下环境中可能存在的多种障碍物，影响多自主式水下机器人（AUV）集群运动规划问题，提出一种基于人工势场的多AUV集群实时避障方法。[**方法**] 首先，采用一种基于动态网络拓扑的编队方法，将AUV看作网络中的节点，通过设置势场函数来满足编队要求；然后，基于人工势场法对同时存在目标和障碍的区域建立势场函数，并将势场函数改进为指数函数，对AUV进行在线规划，实时完成多AUV集群避障的任务；最后，在Matlab软件中仿真设置10台AUV和6个障碍物进行仿真验证。[**结果**] 仿真结果表明，采用该方法，AUV可以全部顺利地避开障碍物，准确到达目标点的安全区域。[**结论**] 人工势场函数法可准确实现多AUV的实时避障，该技术的进步对提高军事作战能力具有重要的意义。
关键词：自主式水下机器人；人工势场；集群运动；编队控制；避障

[*Continued from page* 37]

自主式水下机器人水下对接技术综述

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摘 要：自主式水下机器人（AUV）作为水面支持平台和海底空间站以及深海长期观测系统之间的重要纽带，其水下对接技术一直以来都是国内外的研究热点。在归纳、分析国内外AUV水下对接技术如水下箱（笼）式对接、机械手或载体辅助式对接、杆类引导对接、平台阻拦索式对接和喇叭口式引导对接技术的基础上，介绍各种AUV对接技术的实现方法和结构原理，以及对接技术的发展现状与趋势。并针对目前应用较为广泛的喇叭口式引导对接方式，详细介绍一种针对重型AUV的水下对接系统。经试验验证，该系统模块化强，对横滚姿态要求低，适用于多种尺寸AUV，对接系统的对接成功率高。所做工作可为今后AUV水下对接技术的发展提供参考。
关键词：自主式水下机器人；水下对接；结构原理；喇叭口式引导对接；综述