An Overview of Submersible Research and Development in China

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Abstract

Given the recent success in the development of several submersibles in China, people's interest in the history of submersible development is increasing. This paper presents the history of submersible development in China, which can be briefly divided into three periods. The first one is the early period of hardship (1971–2000). Many prototype submersibles of HOVs, ROVs, and AUVs were developed at this time, but the main achievement was the establishment of special research organizations and the training of research and development personnel. The second period can be regarded as the quick development period (2001–2015). All currently used submersibles were developed during this period. The most remarkable achievement was the successful development of 7000 m-deep manned submersible “Jiaolong.” The third period aims to develop 11 000 m submersibles for challenging the full ocean depth (2016–2020). In this period, two unmanned submersibles and two manned submersibles will be the significant indicators of achievement. If this 5-year plan can be successfully completed, China can play a significant role in the investigation of the deepest part of the oceans, namely, the hadal trenches (6500–11 000 m).

Keywords Hadal trenches · Submersibles · Deep tow system · Lander · Glider · Autonomous and remotely operated vehicle (ARV) · Human-occupied vehicle (HOV) · Full ocean depth (FOD)

1 Introduction

Conflict among population, resources, and the environment in the twenty-first century has made the ocean a strategic space and resource treasure of human society to realize sustainable development. To study the ocean environment and exploit ocean resources, a fundamental understanding of complex and interwoven ocean processes across a broad range of spatial and temporal observational scales is required. Various research fleet and equipment are necessary to support increasingly complex, multidisciplinary, multi-investigator research projects, including those in support of autonomous technologies, ocean observing systems, process studies, remote sensing, and

modeling (CENORF 2009). Various underwater submersibles are the main working force for the research fleet. A submersible is a small vehicle designed to operate underwater. The term submersible is often used to differentiate from other underwater vehicles known as submarines; a submarine is a fully autonomous craft that can renew its own power and breathe air, whereas a submersible is usually supported by a surface vessel, platform, shore team, or large submarine. Submersibles can be divided into human-occupied vehicles (HOVs), remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), hybrid ROV and AUV (HROV or ARV), and gliders. An HOV also known as a manned submersible (MS) is a type of submersible that can carry scientists, engineers, various electronic devices, and special equipment to arrive at various complex deep sea environments quickly and accurately. This vehicle can conduct efficient exploration, scientific investigation, and other deep sea operations. It is an important technical means to understand ocean phenomena and exploit ocean resources. A typical MS consists of four major components: a pressure hull, propellers (thrusters), buoyant materials, and observational and sampling instruments. Currently, the four types of different HOVs are MS, deep submergence rescue vehicle (DSRV), atmospheric diving suit (ADS), and rescue bell. An ROV is a tethered underwater robot that allows the vehicle's operator to remain in a comfortable environment while the

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ROV works in a hazardous environment below. The total ROV system comprises the vehicle, which is connected to the control van and operates on the surface by a tether or umbilical; a group of cables that carry electrical power, video, and data signals back and forth between the operator and vehicle; a handling system to control cable dynamics; a launch system; and associated power supplies. High power applications often use hydraulics in addition to electrical cabling. In many cases, the umbilical includes additional strength members to allow recovery of heavy devices or wreckage. The most commonly known unmanned underwater vehicle is the autonomous underwater vehicle (AUV). AUVs can be used for underwater survey missions such as detecting and mapping submerged wrecks, rocks, and obstructions that can be a hazard to navigate for commercial and recreational vessels. An AUV conducts its survey mission without operator intervention. When a mission is complete, the AUV will return to a pre-programmed location where the data can be downloaded and processed. Underwater gliders are autonomous vehicles that profile vertically by controlling buoyancy and move horizontally on wings (Rudnick 2015). A division of various submersibles is given in Fig. 1. The uses of these vehicles include offshore petroleum, telephone cable maintenance, science, surveying, salvage, and military functions. Recent overview papers include HOV (Kohnen 2009; Moorhouse 2015), ROV (Christ and Wernli 2014; Teague et al. 2018), AUV (Wynn et al. 2014), HROV (Bowen et al. 2004) or ARV (Deng et al. 2014), glider (Rudnick 2015), deep tow system (DTS) (Marsset et al. 2010), lander (Tenberg et al. 1995), and drifters and floats (Richardson and John 2001).

However, in all these review papers, little information was given about the submersible development in China due to a lack of publications in early times. Furthermore, only two review papers that specifically focused on Chinese activities have been found with partial information, and they are now out of date (Pang et al. 1999; Zhu 2001). Therefore, the present author conducted a comprehensive survey of the development history and current status of various submersibles in China. This work may be useful for newcomers in China or for the international community.

Fig. 1 Division of various submersibles

2 Early Period of Hardship (1971–2000)

2.1 Human-Occupied Vehicle (HOV)

The earliest submersible developed in China was a DSRV named “7103,” which indicated that the project started in March 1971. This submersible was jointly developed by Shanghai Jiao Tong University (SJTU), China Ship Development and Design Center (CSDDC), and Wuchang Shipbuilding Industry Co., Ltd. The submersible was of 15 m length and 35 tons displacement. The maximum design depth was 600 m, but the actual depth reached in sea trials was only 300 m. It was put into service by the Chinese navy in 1987.

In China, governmental funding was run in a 5-year basis, with 1956–1960 as the first 5-year plan. In the sixth 5-year plan period from 1981 to 1985, China Ship Scientific Research Center (CSSRC) developed the first ADS named “QSZ-I” for the Chinese navy. In the next 5 years from 1986 to 1990, CSSRC continued the development of another improved ADS named “QSZ-II.” Both of them are of 300 m diving depth.

From 1991 to 1995, Harbin Engineering University (HEU) in cooperation with CSDDC developed a torpedo salvage vehicle “Yuying.” It was a MS of 200 m diving depth. From 1996 to 2001, CSSRC developed a rescue bell of 200 m depth.

2.2 Remotely Operated Vehicle (ROV)

In the late 1970s and early 1980s, Shenyang Institute of Automation (SIA) of the Chinese Academy of Sciences (CAS) in cooperation with SJTU started to develop the first ROV “HR-01” in China. This project was completed in the sixth 5-year period. It was an ROV of 200 m diving depth. In the next 5-year period from 1986 to 1990, SJTU continued the development of ROV “HR-02” while SIA developed “Recon IV” ROV; both vehicles are of 200 m diving depth. Subsequently, SIA focused on the development of AUV, whereas SJTU continued the development of ROV of HR series such as HR-03 and HR-04. All these vehicles can be regarded as the prototypes of ROVs, and they have not been put into service.

In the 8th 5-year plan from 1991 to 1995, CSSRC finished the development of a 600-m ROV “8A4.” It successfully completed sea trials but was not put into service.

2.3 Autonomous Underwater Vehicle (AUV)

The first AUV developed in China was called “Explorer,” and its maximum diving depth was 1000 m. It was jointly developed by SIA, CSSRC, and Institute of Acoustics (IOA) of the CAS from 1991 to 1994. From 1992 to 1997, the AUV team in cooperation with Russia developed the first 6000-m AUV

named “CR-01” under the support of the Ministry of Science and Technology (MOST); from 1998 to 2002, an improved 6000-m AUV named “CR-02” was further developed. Both “CR-01” and “CR-02” finished sea trials with a maximum diving depth of 5280 m, but these two submersibles have never been put into service due to various reasons.

Similarly, HEU started to develop AUVs for military use. They developed the “Zhishui I” prototype in 1992, “Zhishui II” in 1995, and “Zhishui III” in 2000.

2.4 Early Four Main Research Organizations

Although the development of various submersibles in China started as early as the 1970s, progress was initially slow. Almost all the submersibles developed were prototypes due to various reasons, and they did not play any significant role in deep sea studies. However, four organizations formed a special division for submersible development. These organizations are CSSRC, which mainly focused on HOV under the leadership of Xu Qinan (1936–present), now an academician of Chinese Academy of Engineering (CAE); SJTU is strong in ROV under the leadership of Zhu Jimao (1936–present); SIA is dominant in scientific AUV under the leadership of Jiang Xinsong (1931–1997), a former academician of CAE; and

HEU is mainly for military AUV development under the leadership of Xu Yuru (1942–2012), a former academician of CAE. From 1996 to 2000, SJTU developed the first 6000-m DTS named “SJTU-ST6000” in China. Figure 2 shows a list of submersibles developed in this first period, during which few publications were made internationally (Pang et al. 1999; Zhu 2001). Therefore, little influence was caused in the international community about submersible development in China.

3 Quick Development Period (2001–2015)

3.1 Urgent Need of Various Submersibles by China Ocean Mineral Resources R&D Association (COMRA)

In the late 1990s, the International Seabed Authority (ISA) started the draft of regulations on prospecting and exploration for polymetallic sulphides and cobalt-rich ferromanganese crusts. COMRA is the Chinese representative in ISA, and they urgently needed various submersibles to explore international oceans. On the basis of the experience of various submersible developments in the early period, COMRA sponsored SJTU in 2001 to develop a workable ROV of 3500 m depth named “Hailong.” The first one was lost in sea trials due to cable

Fig. 2 Representative prototype submersibles developed in China from 1971 to 2000

breakage, and the team continued to develop a second one. “Hailong II” successfully finished sea trials and was put into service in 2009. At the same time, COMRA successfully persuaded the MOST to fund the project to develop a deep MS of 7000 m depth. This project was coordinated by COMRA as the final user, and it contained four subprojects: submersible development, the development of a launch and recovery system together with mothership upgrade, the selection and training of pilots for sea trials and future application, and the establishment of future management center for submersible operation. CSSRC, SIA, and IOA are the leader institutes for submersible development, whereas CSDDC is in charge of the development of launch and recovery system together with mothership upgrade. COMRA is responsible for the selection of pilots for sea trials and the establishment of future management centers for submersible operation. In this project, many papers have been published (e.g., Guo et al. 2006; Yu et al. 2007; Pan et al. 2010, 2012; Pan and Cui 2012, 2013; Cui et al. 2013; Wang et al. 2014; Wang et al. 2015a, b; Wang and Cui 2015; Liu et al. 2015; Gao et al. 2016).

From 2011 to 2013, SIA was tasked by COMRA to develop another usable 6000-m class AUV, and this vehicle was successfully constructed. It was named “Qianlong-I” (Wu et al. 2014). In the same period, HEU continued the development of “Zhishui IV” and “Zhishui V” AUVs for the Chinese navy, and several papers about the vehicles’ progress have been published (e.g. Zhang and Chu 2011; Zhang et al. 2011).

Figure 3 shows all these submersibles that have been successfully developed and put into service. Notably, the success of “Jiaolong” has remarkably influenced China’s decision on the development of various submersibles in the following years. Cui (2013) has presented in detail the development process and its technical achievement of the “Jiaolong” submersible.

3.2 Development of 4500-m Class Domestically Made Submersibles

In the 11th 5-year period (2006–2010), a substantial number of people did not believe that the “Jiaolong” submersible

could be successfully developed. Thus, in the 12th 5-year plan, emphasis was placed on 4500 m, which is a practical required depth. One submersible in each category of AUV, ROV, and HOV was sponsored by MOST. The main emphasis of MOST is that more than 90% equipment must be built in China due to the technical blockage previously met in the development of “Jiaolong.” One of each ROV, HOV, and AUV was initiated in 2008, 2009, and 2010, respectively, by MOST. The ROV (“Haima4500”), HOV (“Shen Hai Yong Shi [Deep Sea Warrior],” and AUV (“Qianlong II”) finished sea trials in 2014, 2017, and 2016, respectively (Fig. 4). Several papers have been published concerning the development of Haima 4500 ROV (Fan et al. 2012; Lian et al. 2015; Tao and Chen 2016; Ping et al. 2017).

3.3 Development of Hybrid Submersibles, Gliders, Landers, DTSSs, and Deep Floats

Given the increased support from MOST for various submersibles, an increasing number of research organizations have started to conduct various studies and developments for different submersibles. When WHOI started the development of the hybrid concept of AUV and ROV (Bowen et al. 2004), some researchers from SJTU, CSSRC, and SIA began to explore this concept as well. In 2006, they jointly persuaded the Ministry of Industry and Information Technology (MIIT) to sponsor a project to develop a similar unmanned submersible named “Nereus.” This concept was first proposed by McFarlane in 1990 (McFarlane 1990) and implemented in Japan as a 7000 m class expendable optical fiber cable ROV (UROV7K) (Nakajoh et al. 1998). The main idea of HROV is that it will operate in two different modes. For broad area survey, the vehicle will operate in fully autonomous, untethered mode and map the seafloor with sonars and cameras. After targets of interest have been found, the vehicle will be converted at sea to an ROV mode that will permit close-up imaging and sampling. The ROV mode will include an add-on capability for cameras, lights, a manipulator, and sampling gear. In the ROV mode, a lightweight fiber optic cable to the surface will permit the high bandwidth feedback to the surface

Fig. 3 Photos of three submersibles, namely, “Hailong,” “Qianlong I,” and “Jiaolong”

Hailong II

Qianlong I

Jiaolong

Fig. 4 Three 4500-m class submersibles

Haima4500

Qianlong II

Shen Hai Yong Shi

to permit high-quality teleoperation (Bowen et al. 2004). In China, this vehicle was called autonomous and remotely operated vehicle (ARV) (e.g. Li et al. 2011; Feng et al. 2011; Deng et al. 2014). Both CSSRC and SIA retreated from the project because of inadequate funding and other reasons, but SJTU continued the development. Prototype development was completed after a lake test in 2012, and the ARV was named “Long Huang” (Deng and Ge 2012; Wang et al. 2013a, b). This submersible has now been updated and renamed to “Hailong11000.” It has just finished 4000-m depth sea trials in April 2018, and it will continue to undergo sea trials next year.

SIA received additional support from MOST and started the development of a 100-m depth ARV named “Arctic” because its main mission was working under ice (Li et al. 2011). Simultaneously, CSSRC started the development of 300 m class “Haizheng” (Xu et al. 2010). The first prototype was completed in 2012, and CSSRC received an order from Shanghai Maritime University (SMU) to develop another one. It was initially named “Haizheng II” but later changed to “Haishi (Maritime)” (Deng et al. 2014).

In 2016, Shanghai Ocean University (SHOU) developed the “Rainbowfish” ARV (Cui et al. 2017) while SIA developed “Hadal” ARV; both vehicles were for 11 000 m depth. “Hadal” ARV successfully reached the Challenger Deep in 2016, but it was lost in an operation during a cruise the following year. “Rainbowfish” ARV underwent second sea trials in the cruise from December 2016 to February 2017, but the maximum diving depth reached was only 6300 m due to various problems.

Since 2003, SIA started to develop the first glider in China. The prototype completed lake trials in 2006, and SIA received funding support to develop the “Haiyi” series of gliders in 2007. In 2009, 300-m depth sea trials were completed (Yu et al. 2011). Thereafter, they developed gliders for deeper depths, and the glider that could reach the deepest parts was “Haiyi7000” (Chen et al. 2015a, b, c). She successfully reached 6329 m in the Marina trench in March 2017, and that depth remains the current maximum depth a glider has ever reached. In Tianjin University (TU), another group under the leadership of Professor Shuxin Wang started to develop “Hai Yan” series in 2006; they have also achieved great success (Wang et al. 2007, 2009; Liu et al. 2014a, b; Lei et al. 2016a, b; Ma et al. 2016; Wang et al. 2017; Wu et al. 2017).

The maximum diving depth reported is 1500 m, and they have received numerous orders for massive production. CSSRC started the development of gliders in 2012, and their second glider “Haixiang” reached a depth of 503 m in 2016 (Chen et al. 2015a, b, c). In addition to these organizations, many other groups have expressed interest in developing various specific-purpose gliders. They include Northwestern Polytechnical University (Tian et al. 2012), Zhejiang University (Fan and Woolsey 2013; Fan et al. 2014; Yang et al. 2014), Hangzhou Dianzi University (Chen et al. 2015a, b, c), SJTU (Yang and Ma 2010; Cao et al. 2015), Ocean University of China (OUC) (Fan et al. 2016), and National Ocean Technology Center (NOTC) (Qi et al. 2013).

DTS is a comprehensive observation instrument system towing under a ship for deep sea geology and geophysics. It is usually equipped with a precision navigation and positioning system, which consists of a side scan sonar, narrow beam precision echo sounder, profiler, magnetometer, stereo camera, continuous temperature measuring device, substrate or biological sampler, and other geological and geophysical observation instruments (Marsset et al. 2010). As previously mentioned, SJTU developed the first 6000-m SJTU-ST6000 in 1999. Under the support of MOST, the IOA developed another two 6000-m DTSs in the period of 2001 to 2015.

“Lander” is a general term for any autonomous, unmanned oceanographic research vehicle that free falls to the sea floor unattached to any cable and then operates independently on the sea floor. At the end of deployment, ballast weights are released either by a pre-programmed timing device or on an acoustic command transmitted from the surface. The lander then floats back up to the surface by virtue of its positive buoyancy. Other terms that have been used for such devices are “free-fall vehicle” and “pop-up vehicle” (Tenberg et al. 1995). In the period of 2011 to 2013, SIA developed the first lander of 3000 m depth named “Cold sweep.” They then developed two other FOD landers named “Tianya” and “Haijiao” from 2013 to 2016. In the same period, SHOU developed three different “Rainbowfish” series FOD landers. All these five landers have successfully reached the Challenger Deep in 2016.

NOTC has conducted research and development of drifters and floats since 1999; in 2003, they successfully finished

2000-m depth sea trials of class float “China Ocean Profiling Explorer (COPEX)” (Yu 2003; Yu et al. 2005). In 2005, No. 710 Institute (710 Institute) of China Shipbuilding Industry Cooperation (CSIC) developed another 2000-m depth class float “HM2000” (Lu et al. 2016). Currently, OUC, SJTU, and SHOU are starting the development of 4500-m depth class floats.

4 Challenge of the FOD Period (2016–2020)

4.1 FOD Submersibles Under Development in China

After the success of the “Jiaolong” deep MS in 2012, many people predicted that the focus in the 13th 5-year period will be FOD. They then started the preparation for the proposal to MOST for developing FOD submersibles. CAS set up a specific research project in 2013 to develop FOD landers and ARV. The “Hadal” ARV and two landers “Tianya” and “Haijiao” are the result of this project. The present author was invited by SHOU to establish a Hadal Science and Technology Research Center (HAST) to specifically focus on hadal zones. To speed up development, HAST introduced a new funding mode called “governmental support+private investment” and worked in close cooperation with Shanghai Rainbowfish Ocean Technology Co. Ltd. (RFOT). They intended to develop a comprehensive investigation system for the survey of hadal trenches (Cui et al. 2014; Cui 2015; Cui and Wu 2018). The system consists of three FOD landers, one FOD ARV, one FOD HOV, and a 4800-ton displacement mothership. The construction of the first phase of this comprehensive investigation system has been completed. Figure 5 shows an image of this comprehensive investigation system, which includes three “Rainbowfish” series landers, one “Rainbowfish” ARV, and the mothership “Zhang Jian.”

Fig. 5 ARV (front) and three landers (behind) on the mothership “Zhang Jian”

In 2016, their speculations were confirmed (Cyranoski 2016; Qian et al. 2016). Aiming at the important national demands in exploring deep oceans, exploiting deep ocean resources, and safeguarding ocean rights, MOST focused their funding support in the two main lines of deep sea science and technology. One is to develop 11 000-m-deep sea technology and become a country of sea power. The second is to improve the basic research level and original innovation ability of deep sea technology; form equipment with 1000–7000-m-level deep sea carrying and detecting, pedigree, localization, and supporting ability; and promote the development of deep sea technology and equipment industry. In this 13th 5-year period, MOST sponsored the development of two FOD ARVs and one HOV. After competition, SJTU and SIA will be the leading organizations responsible for developing one of the two ARVs, whereas CSSRC is the leading organization responsible for developing the FOD HOV. Although HAST did not win support from MOST, they continued the development of FOD HOV “Rainbowfish” with the support from various local governments and private investment to RFOT. Since 2018, RFOT has also invested in developing another 6000-m HOV to form a fleet that aims to provide better services to ocean scientists with capability of full ocean areas and FOD.

In addition to supporting these FOD submersibles, MOST has also funded other submersibles to complete the spectrum of submersibles. Scientists in China have defined five depth levels for the spectrum, namely, 500, 2000, 4500, 7000, and 11 000 m (Qian et al. 2016).

4.2 Main Technical Challenges for the Development of FOD Submersibles

The most challenging aspect of the development of various submersibles is the development of the FOD HOV because almost all the technology challenges encountered in the development of unmanned submersibles are covered by the HOV. Unmanned submersibles plus manned cabins are approximately equal to HOV. Both landers and ARV can be regarded as the test platforms for the development of the FOD HOV (Cui et al. 2014). The key technical issues solved in the development of ARV have been described in Cui et al. (2017).

The key technical issues to be solved for the development of the FOD HOV and their current progresses in China are described briefly in this section. The specific technical challenges for ROV and AUV or multi-AUVs can be found in Christ and Wernli (2014) and Vedachalam et al. (2018), respectively.

The most challenging issue is related to design, that is, how global optimum performance can be achieved. The design of the FOD HOV is a multidisciplinary issue that involves the compromise or optimization of many objectives and constraints. Thus, it is a multidisciplinary design optimization (MDO) issue. Two problems need to be addressed in this aspect. One is how to build the MDO mathematical model,

Table 1 HOVs developed in China

Name	Design depth/m	Development period	Chief organization for the development	Sponsor	User	Other important information
7103 DSRV	600	1971–1987	SJTU	Navy	Navy	Maximum sea trial depth 300 m
QSZ-I ADS–	300	1981–1985	CSSRC	Navy	Navy	
QSZ-II ADS	300	1986–1990	CSSRC	Navy	Navy	
Yuying Torpedo salvage	200	1991–1995	HEU	Navy	KSERTC	
Rescue Bell	200	1996–2001	CSSRC	Navy	Navy	
Mobile Rescue Bell	200	2003–2005	CSSRC	Navy	Navy	
Jiaolong	7000	2002–2013	CSSRC	MOST	NDSC	
Shen Hai Yong Shi	4500	2009–2017	CSSRC	MOST	IDSE	
QSZ-III ADS	500	2011–2015	CSSRC	MOST	CNOOC	
Rainbowfish	11 000	2013–2021	SHOU	SHOU/RFOT	RFOT	
–	11 000	2016–2021	CSSRC	MOST	IDSE	

and the other is how to efficiently and accurately solve the mathematical problem. In the design of the “Jiaolong” deep MS, Cui and his group started to explore the possibility of applying MDO theory to design deep MSs, and many papers have been published in this aspect (e.g., Gou and Cui 2010; Zhao and Cui 2011; Zhao et al. 2015; Pan and Cui 2014). Moreover, a book was recently published about this concern (Pan and Cui 2017).

A comprehensive optimization design of the hydrodynamic layout for the FOD HOV is also required to achieve a high descent/ascent rate. To address this issue, the traditional approach of numerical computation with model tests is still applicable (Li et al. 2013). Jiang and Cui (2015) reported the optimization of the “Rainbowfish” HOV.

Furthermore, ergonomic interior design of a manned cabin must be implemented. The manned capsule is the working and living area for pilots and scientists. Given that the cabin must withstand extremely high FOD pressure and an industrial limitation exists for manufacturing large and thick manned cabins, the internal diameter of the manned cabin is only 2.1 m for “Rainbowfish” FOD HOV. This value is already the largest for existing three-person manned cabins for deep MSs. The diameter of the manned cabin for another FOD HOV sponsored by MOST is 1.8 m. Maximizing the cabin design advantages of existing MSs and improving the comfort of crews within the small and closed environment is a critical issue. To date, no toilet has been equipped in any manned cabin, which is a main

Table 2 ROVs developed in China

Name	Design depth/m	Development period	Chief organization for the development	Sponsor	User	Other important information
HR-01	200	1981–1985	SIA	MOST	SIA	
HR-02	200	1986–1990	SJTU	–	SJTU	
HR-03	–	1991–1995	SJTU	–	SJTU	
HR-04	–	1996–2000	SJTU	–	SJTU	
RECON IV	200	1986–1990	SIA	–	SIA	
8A4	600	1991–1995	CSSRC	MOST	CSSRC	
Hailong I	3500	2001–2005	SJTU	COMRA	–	Lost in the sea trial in 2003
Hailong II	3500	2005–2009	SJTU	COMRA	COMRA	
Hailong III	6000	2016–2018	SJTU	COMRA	COMRA	
Haima4500	4500	2008–2014	SJTU	MOST	Guangzhou Marine Geological Survey (GMGS)	
Haima500	500	2010–2014	SJTU	SOA	SJTU	
Haixiang1500	1500	2012–2015	SJTU	MOST	CNOOC	
AUTO2000	2000	2015–2018	SJTU	MOST	AVI	
Discovery	6000	2013–2017	SIA	CAS	IDSE	
–	11 000	2017–2025	SJTU	MOST	NDSC	

Table 3 AUVs developed in China

Name	Design depth/m	Development period	Chief organization for the development	Sponsor	User	Other important information
Explorer	1000	1991–1994	SIA	MOST	SIA	
CR-01	6000	1992–1997	SIA	MOST	SIA	
CR-02	6000	1998–2002	SIA	MOST	SIA	
Zhishui I	100	1990–1992	HEU	Navy	HEU	
Zhishui II(7B8)	100	1991–1995	HEU	Navy	HEU	
Zhishui III	300	1996–2000	HEU	Navy	HEU	
Zhishui IV	300	2001–2005	HEU	Navy	HEU	
Zhishui V	1000	2006–2010	HEU	Navy	HEU	No deep sea trials arranged
Chensha	2000	2011–2015	HEU	MIIT	CNOOC	
Qianlong I	6000	2011–2013	SIA	COMRA	NDSC	
Qianlong II	4500	2011–2016	SIA	MOST	NDSC	
Qianlong III	4500	2015–2018	SIA	MOST	NDSC	

Table 4 HROVs or ARVs developed in China

Name	Design depth/m	Development period	Chief organization for the development	Sponsor	User	Other important information
Hailong11000	11 000	2006–	SJTU	MIIT	SJTU	4000-m sea trials completed in April 2017
Arctic	300	2007–2008	SIA	MOST	SIA	
Haizheng I	300	2010–2012	CSSRC	CSSRC	CSSRC	
Haishi/Haizheng II	300	2011–2014	CSSRC	SMU	SMU	
Hadal	11 000	2013–2017	SIA	CAS	IDSE	10 767 m (2016); 10 888 m (2017)
Rainbowfish	11 000	2013–2019	SHOU	SHOU	RFOT	Sea trials reached 6300 m (2017)
–	11 000	2016–2020	SJTU	MOST	NDSC	
–	11 000 m	2016–2020	SIA	MOST	IDSE	

restriction for the time limit of the bottom operation. In the “Rainbowfish” manned cabin, we propose one that is equipped with a toilet. The team is currently working on the interior design and additional tests.

In terms of the components manufactured for the development of an FOD HOV, the most critical components are the manned cabin, buoyancy material, battery, and high

pressure pump/electronic DC motor. These parts are briefly discussed as follows.

For a manned cabin capable for three persons to work at FOD, a comparative study was carried out for several possible candidate materials (Cui et al. 2015); results demonstrated that only 1100 MPa grade ultra-high strength titanium alloy or 1700 MPa level of ultra-high strength steel is feasible.

Table 5 Gliders developed in China

Name	Design depth/m	Development period	Chief organization for the development	Sponsor	User	Other important information
Haiyi 300	300	2003–2009	SIA	MOST	SIA	
Haiyi1000	1000	2010–2014	SIA	MOST	SIA	
Haiyi7000	7000	2015–2017	SIA	MOST	SIA	Maximum sea trial depth 6329 m (2017)
Haixiang	500	2012–2016	CSSRC	SOA	CSSRC	Maximum sea trial depth 503 m (2016)
Hai Yan	1500	2009–2014	TU	MOST	TU	Many products have been finished

Table 6 DTSSs developed in China

Name	Design depth/m	Development period	Chief organization for the development	Sponsor	User
SJTU-ST6000	6000	1996–1999	SJTU	COMRA	COMRA
DTA 6000-I	6000	2001–2014	IOA	MOST	COMRA
DTA 6000-II	6000	2001–2015	IOA	MOST	COMRA

Table 7 Landers developed in China

Name	Design depth/m	Development period	Chief organization for the development	Sponsor	User
Cold sweep	3000	2011–2013	SIA	MOST	SIA
Tianya	11 000	2013–2016	SIA	CAS	IDSE
Haijiao	11 000	2013–2016	SIA	CAS	IDSE
Rainbowfish I	11 000	2013–2016	SHOU	SHOU	RFOT
Rainbowfish II	11 000	2013–2016	SHOU	SHOU	RFOT
Rainbowfish III	11 000	2013–2016	SHOU	SHOU	RFOT

However, for both materials, the welding performance is generally lower than that of the parent metal. To maximize ultra-high strength material properties, welding should be avoided as far as possible. By considering the maturity and economics for these two materials, ultra-high strength steel is chosen for “Rainbowfish” FOD HOV because both MIR I and MIR II used this material for more than 30 years, and their manned cabins remain in good condition (Wang et al. 2016a, b). Another FOD HOV was constructed with ultra-high strength titanium alloy (Lei et al. 2016a, b). Designing windows that fully satisfy the requirements of ASME PVHO (2007) is feasible. In MIR’s experience, after a discussion with MIR’s chief designer and MIR’s pilot, three of us believe that the ASME rule is conservative. Thus, in the design of the manned cabin of “Rainbowfish,” a new safety standard for windows is adopted; many tests need to be arranged to prove the validity of this new standard, and they are currently underway (Du et al. 2017).

In deep MSs, buoyancy is finely tuned through the use of a high pressure seawater pump. Buoyancy is adjusted by pumping sea water into or out of the tanks. The development of a reliable large-flow pump is quite challenging. Liu et al.

(2014a, b) successfully developed a high pressure seawater pump for 4500 m HOV “Shen Hai Yong Shi,” and they are currently working on the 11 000-m HOV pump. In this variable ballast system, the design of a high-power oil-filled brushless DC motor is also a challenge (Hu et al. 2017).

The selection of a battery for MSs is another problem that needs to be considered. Previous MSs used lead acid, nickel cadmium, and silver zinc batteries; the current trend is the use of lithium ion batteries. In Shinkai 6500-m-deep MS, the lithium ion battery has been successfully used for many years (Ogura et al. 2004). In China, the lithium ion battery was successfully applied in “Shen Hai Yong Shi,” and another project for the application of the lithium ion battery in FOD HOV was sponsored by MOST in 2016. We expect that battery technology will show rapid development in this decade, and powerful types of new batteries will occur in the near future.

The density of the buoyancy material exerts great effects on the total weight of the HOV. We have tested all the available buoyancy materials from international companies (Trelleborg Offshore Boston www.Trelleborg.com/AEM, Engineered

Table 8 Floats developed in China

Name	Design depth/m	Development period	Chief organization for the development	Sponsor	User
COPEX	2000	1999–2003	NOTC	MOST	NOTC
HM2000	2000	2001–2005	710 Institute	MOST	710 Institute
–	4500	2016–2019	OUC	NSFC	OUC
–	4500	2016–2019	SJTU	NSFC	OUC
Rainbowfish	4500	2015–2018	SHOU	RFOT	RFOT

Syntactic Systems www.esyntactic.com, Ron Allum Deepsea Services (RADS www.ronallum.com)) and two Chinese manufacturers, Marine Chemical Engineering Institute (Liang et al. 2016) and Technical Institute of Chemistry and Physics of the CAS (Wang et al. 2016a, b); all of them failed to satisfy the requirements of China classification society (Cui et al. 2018). Thus, a definition of its safe life will depend on the water absorption performance, and the selected buoyancy material needs to go through a complete test for its water absorption performance. Such work is underway via the Rainbowfish project.

Tables 1, 2, 3, 4, 5, 6, 7 and 8 provide a summary of all the submersibles developed in China, type by type. All the abbreviations used in tables are summarized here. Deep submergence rescue vehicle (DSRV), atmospheric diving suit (ADS), COPEX. Shanghai Jiao Tong University (SJTU), China Ship Scientific Research Center (CSSRC), Harbin Engineering University (HEU), Kuming Shipborne Equipment Research & Test Center (KSERTC), Ministry of Science and Technology of the People's Republic of China (MOST), National Deep Sea Center (NDSC), Institute of Deep-sea Science and Engineering (IDSE) of the CAS, China National Offshore Oil Corp. (CNOOC), Shanghai Ocean University (SHOU), Shanghai Rainbowfish Ocean Technology Co. Lt. (RFOT), Shenyang Institute of Automation (SIA) of the CAS, China Ocean Mineral Resources R&D Association (COMRA), Guangzhou Marine Geological Survey bureau (GMGS), State Oceanic Administration (SOA), AutoSubsea Vehicles Inc. (AVI), Ministry of Industry and Information Technology of the People's Republic of China (MIIT), Shanghai Maritime University (SMU), Tianjin University (TU), Institute of Acoustics (IOA) of the CAS, National Ocean Technology Center (NOTC), No. 710 research institute (710 Institute) of China Shipbuilding Industry Cooperation (CSIC), Ocean University of China (OUC), and National Science Foundation of China (NSFC). This review demonstrates that Chinese deep sea technology has achieved great progress with the success of the Jiaolong deep MS. After this 5-year plan, they are capable of developing all FOD submersibles. China may become the first country in the world that owns an operational FOD HOV.

5 Summary

In this paper, the Chinese history of submersible research and development has been briefly reviewed. After a long period of hardship, China has already developed many practically used submersibles such as “Hailong II” of 3500 m and Hailong III of 6000 m ROV, “Haima” of 4500 m ROV, “Qianlong I” of 6000 m AUV, “Qianlong II” and “Qianlong III” of 4500 m AUV, “Jiaolong” of 7000 m HOV, and five FOD landers. Two

FOD unmanned submersibles and two FOD MSs are currently under development. Given these achievements, China can play a significant role in the investigation of the deepest oceans, namely, the hadal trenches (6500–11 000 m).

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