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Manned Submersibles—Deep-sea Scientific Research and Exploitation of Marine Resources

Abstract

The successful development and good application of the deep-sea manned submersible Fendouzhe (Striver in English) has significantly improved China's R&D capabilities of technical equipment and the level of independent innovation in manned deep diving, and also made outstanding contributions to accelerating the construction of a maritime power. The 21st century is the "Century of the Ocean", and the rich resources in the ocean is a precious wealth that supports the sustainable development of mankind. The development and utilization of marine resources has become an inevitable trend in the development of all countries. However, the scientific expedition equipment needs to be more specialized for developing deep sea resources. To this end, this article reviews the development of manned submersibles in various countries around the world, summarizes the working performance and key technology development of current manned submersibles in the world, and also analyzes the current development status of our country's manned submersibles and their core technologies. It then puts forward suggestions for future development, hoping to provide insights into accelerating the building of a world marine science and technology powerful nation.

Keywords

manned submersible; marine resources; deep-sea scientific research; marine resource development

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Manned Submersibles—Deep-sea Scientific Research and Exploitation of Marine Resources

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Abstract: The successful development and good application of the deep-sea manned submersible Fendouzhe (Striver) has significantly improved China's R&D capabilities of technical equipment and the level of independent innovation in manned deep diving, and also made outstanding contributions to accelerating the construction of a great maritime country. The 21st century is the "Century of the Ocean", and the rich resources in the ocean are precious wealth that supports the sustainable development of mankind. The development and utilization of marine resources has become an inevitable trend in the development. However, the scientific expedition equipment needs to be more specialized for developing deep sea resources. To this end, this article reviews the development of manned submersibles in various countries, summarizes the working performance and key technology development of current manned submersibles, and analyzes the current development status and the core technologies of China's manned submersibles. We then put forward suggestions for future development, hoping to provide insights into accelerating the building of a great nation in marine science and technology.
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The ocean is the origin of life on Earth. The rich marine resources provide valuable materials to support the sustainable development of the human society, and the exploitation of marine resources has become essential for the development of countries [1]. The study of deep-sea is necessary for answering major scientific questions such as the origin of life and the evolution of the Earth. Although humans have traveled into space, little is known about the oceans that are close to us since the deep-sea environment is featured by darkness, high pressure, low temperature, and complex topography. Another reason is the lack of efficient manned submersibles as operational tools for deep-sea scientific research and marine resource exploitation.

This paper focuses on the technologies of manned submersibles for deep-sea scientific research [2]. Since the development of manned submersible Alvin in 1964 in the United States, developed countries have been committed to the study of manned submersibles and made great achievements. Although the research on manned submersibles in China started late, the breakthroughs and achievements made in recent years have attracted worldwide attention [3]. Despite the long-term technical constrains, China has successively developed manned submersibles Jiaolong, Shenhai Yongshi (Deep-Sea Warrior), and Fendouzhe (Striver), which have gradually reached the top tier of manned submersible technologies in the world.

1 Development status of manned submersibles

Deep-sea vehicle can carry sonar devices, mechanical sampling devices, submariners, and scientists, and quickly and accurately access various deep-sea environments for scientific expedition. Deep-sea vehicles are mainly classified into two categories: human occupied vehicle (HOV) and unmanned underwater vehicle (UUV). The latter can be further divided into remotely operated vehicle (ROV) [4], autonomous underwater vehicle (AUV), the newly emerged autonomous and remotely operated vehicle/hybrid remotely operated vehicle (ARV/HROV), and unpowered submersibles. As a multi-purpose underwater mobile platform, deep-sea vehicle can be equipped with devices for accurate operation, thus becoming an epitome of devices for deep-sea scientific research.

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1.1 Development of manned submersibles in the world

The world's first manned deep-sea submersible [5], Trieste I, was developed in 1960 and dived to a maximum depth of 10 916 m in the Challenger Deep, making it the manned submersible with the maximum diving depth. Despite the remarkable achievement, the submersible, with a displacement of over 50 t, was too large and extremely difficult to be built and transported. Furthermore, the submersible cannot navigate and operate underwater due to the technical constraints at that time. As a result, the submersible had no practical application in scientific research, except for breaking the record of human diving and being used for expeditions. Since the 1960s, the devices of submersibles have been advanced, and most submersibles are equipped with manipulators, scientific instruments, and larger observation windows.

In 1964, the modern manned submersibles represented by Alvin developed in the United States [6] initiated the scientific expedition on the seafloor. Alvin was equipped with advanced detection devices such as observation windows, high-definition cameras, and acoustic scanning system (Figure 1a). Alvin carried out many important and influential operations in practical voyages, and established the dominant position of the United States in the field of modern manned submersibles. The most notable example is the salvage of a sunk U.S. Navy hydrogen bomb in 1966 with the help of Alvin. In 1977, Alvin identified the first submarine hydrothermal field in the fracture zone of Galapagos Rift, and investigated the typical biological communities around it. In 1985, it located the wreckage of the Titanic. To date, Alvin has completed 5 000 dives, becoming the most frequently used and successful manned submersible in the world, considerably driving the application of manned submersibles in deep-sea scientific research, deep-sea expedition, and military tasks.

Inspired by the great success of Alvin, many countries began to develop their own manned submersibles. The Japanese Shinkai 6500 [7] manned submersible was built in 1989 and conducted a series of manned diving tests, with a maximum diving depth of 6 527 m. It is the manned submersible with the maximum diving depth and the highest operability in Japan. In 1991, Shinkai 6500 began its mission to study seafloor topography and geology and research deep-sea organisms in the Pacific Ocean, Atlantic Ocean, and Indian Ocean, diving for a total of over 1 300 times.

The famous Russian 6000-m manned submersibles MIR-1 (Figure 1 b) and MIR-2 were built in 1987 [8]. They can accommodate 3 people and 12 sets of devices for detecting deep-sea environmental parameters and seafloor topography. These two submersibles are characterized by sufficient power, which is twice that of the American Sea Cliff and the French Nautilus, and they can stay underwater for 17–20 h. In recent years, the MIR series of manned submersibles have always been at the forefront of deep-sea exploration in the world. Since the commissioning in 1987, the MIR series of manned submersibles have been used in a variety of scientific research and expeditions in the Indian Ocean, Pacific Ocean, Atlantic Ocean, and Arctic Ocean. Notably, they accomplished the detection of nuclear radiation from the Communist Youth League nuclear submarine. Meanwhile, the MIR series have been frequently employed to detect the warships sunk in the Second World War, as well as to perform the Arctic-2007 marine survey, demonstrating outstanding technical capabilities.

Europe has built a solid foundation for the development of manned submersibles, mainly by France, Germany, and the United Kingdom. A typical example is the Nautilus 6000-m submersible developed by France in 1985 [9]. It is operatable in 97% of the global waters and has made more than 1 700 dives so far. Nautilus can be used for investigation of deep

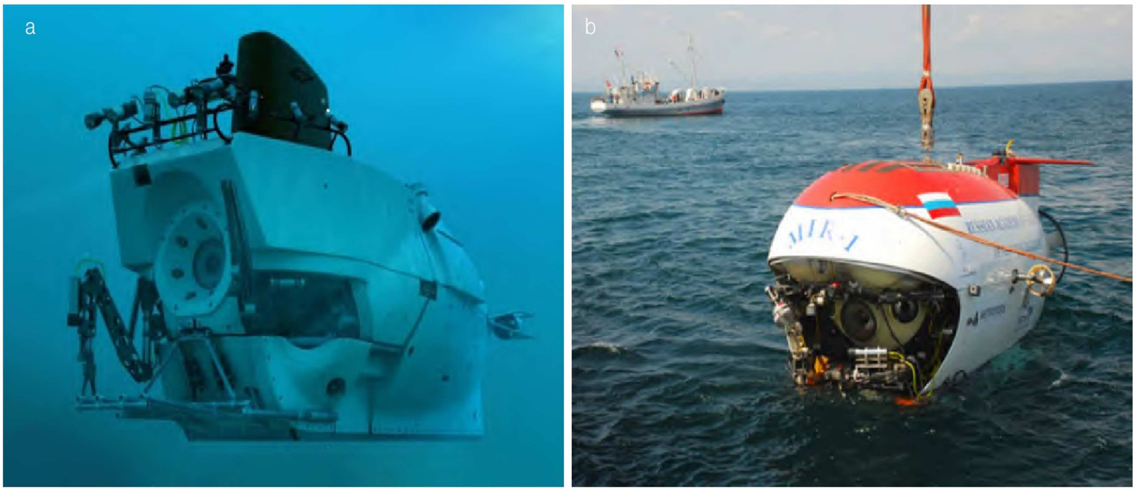

Figure 1 Alvin manned submersible of the U.S. (a) and MIR-1 manned submersible of Russia (b)

seafloor ecology and search for shipwrecks and hazardous wastes, and has been most frequently used in the military field. The light weight, rapid rising and diving, ability of deep sea diving, and a miniature underwater robotic system allow Nautilus to perform multi-dimensional deep-sea scientific expeditions.

1.2 Development of manned submersibles in China

In China, the research on manned submersible started in the 1980s. The first manned submersible 7103 lifeboat was developed in 1986, which was a major research achievement that filled the gap of deep-sea submersible technology in China. This submersible, with the length of 15 m, weight of 35 t, diving depth of 300 m, and speed of 4 knots ①, was the most advanced rescue manned submersible in China at that time. In 1996, based on sea tests and application experience, the submersible was overhauled and upgraded with a four-degree-of-freedom dynamic positioning system and a central control and display system. To meet the demand of naval mine salvage, the 750 Experimental Field of China State Shipbuilding Corporation Limited was equipped with type I and II manned submersibles developed in China, both of which played a critical role in underwater salvage and operation.

To advance the deep-sea submersible technology and accelerate the construction of a great maritime country, China initiated the National High-tech R&D Program ("863 Program") to support nearly 100 Chinese research institutions and enterprises, such as 702 Institute of China State Shipbuilding Corporation Limited, Institute of Acoustics (Chinese Academy of Sciences), and Shenyang Institute of Automation (Chinese Academy of Sciences), to jointly work on the independent design and technical integration of 7 000-m manned submersible on the basis of previous submersible technology and experience [10], overcoming a series of technical hurdles in deep-sea technologies in China. In June 2012, Jiaolong created a record of manned submersible in China by diving to a depth of 7 062 m in the Mariana Trench (Figure 2a), which broke the world dive record of modern manned submersibles for deep-sea operation held by Shinkai 6500 for 23 years. In 2013, Jiaolong officially entered the experimental application stage and achieved world-renowned results. It has carried out scientific research and operation in the South China Sea, the exploration of polymetallic nodules in the East Pacific Ocean, the exploration of seamount crust in the West Pacific Ocean, the exploration of polymetallic sulphides in the Southwest Indian Ridge, the investigation of polymetallic sulphides in the Northwest Indian Ridge, and the scientific research in Yap Trench and Marianas Trench in the West Pacific Ocean. Its excellent technical parameters and performance have been verified during the sea tests. As of November 2018, Jiaolong made 158 successful dives, mainly for scientific research of marine geology, marine geophysics, marine geochemistry, and marine life on complex seafloors. A huge amount of high-precision positioning survey data and numerous high-quality precious geological and biological samples were obtained, which have greatly improved the deep-sea research in China. The well-established deployment and recovery operation mode, a set of safety system, and a large number of professional divers and technical and logistics support teams of Jiaolong have fueled the rapid growth of manned submersible in China.

On the basis of successful development and application of Jiaolong and with the support of "863 Program" during the "Twelfth Five-Year Plan Period", China launched the construction of the second 4,500-m manned submersible named Shenhai Yongshi in 2014 [11]. Based on the accumulated technologies and experience, the project greatly reduced the costs of operation and maintenance and achieved the independent research and development of deep-sea core technologies and key components represented by solid buoyancy material, deep-sea lithium-ion battery, and manipulator, laying a solid foundation for the development of manned submersibles with multiple functions in China.

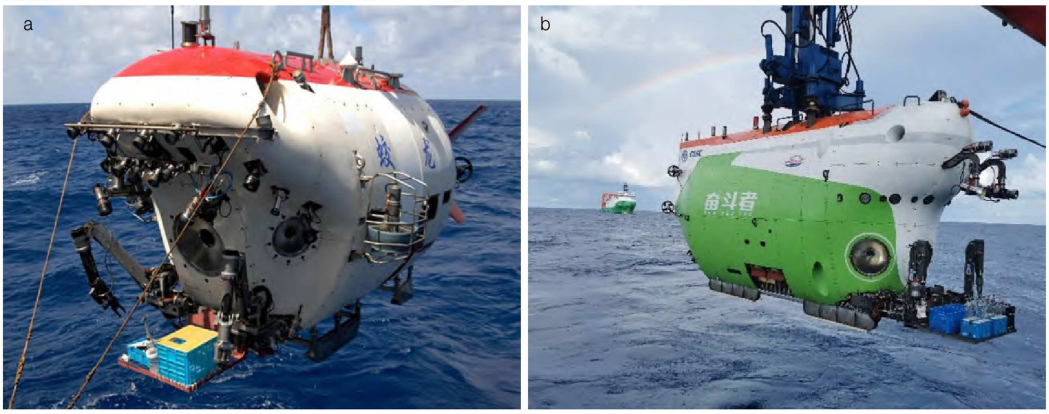

Figure 2 Jiaolong (a) and Fendouzhe (b) manned submersibles of China

① Knot: Unit for the speed of a ship. 1 knot (kn) = 1 nautical mile per hour = 1.852 km/h.

On the basis of the first and second manned submersibles, China launched the development of a full-ocean-depth manned submersible. In 2016, with the support of National Key R&D Program, China initiated the development of a full-ocean-depth manned submersible and related key technologies. A team composed of the talents involved in the development of Jiaolong and Shenhai Yongshi spent five years achieving a number of major technological breakthroughs in pressure structure, titanium alloy material, buoyancy material, acoustic system, intelligent control technology, lithium-ion battery, sea water pump, and manipulator. On November 10, 2020, Fendouzhe dived to a depth of 10 909 m (Figure 2b), a new record of manned submersible in China [12], which marked China as a leader in the development of manned deep-sea submersibles. Fendouzhe is equipped with a high-definition camera and an electric cloud platform for underwater observation, a high-resolution side-scan sonar for bathymetry, an integrated navigation system, a high-speed underwater acoustic communication system, and a manipulator. It adopts a safe, stable, and high-capacity power system, an advanced control and positioning system, and a pressure manned ball cabin with solid buoyancy material. The localization rate of core components of Fendouzhe reached 96.5%. This submersible is capable of full-ocean-depth accessibility for scientific research and operation, and it was on trial in November 19, 2020 [13]. Fendouzhe was delivered to the Institute of Deep-sea Science and Engineering, Chinese Academy of Sciences in March 2021.

2 Performance and core technologies of manned submersibles

Compared with other equipment for deep-sea scientific expedition, manned submersible has many practical advantages. (1) Modern manned submersibles are equipped with well-developed operating systems that are sufficiently powered and portable, and the propeller allows the submersible to navigate freely underwater. The pilot can drive the submersible to the target site for scientific expedition with predetermined coordinates. (2) Modern manned submersibles can carry sampling devices for sampling in deep-sea environment, and the flexible operation with manipulators can realize the real-time sampling and device recovery on seafloor at a depth of 10 000 m. (3) Several scientists can be carried into the deep-sea environment. Through observation windows, scientists can observe the deep-sea environment at a close range and make long and continuous observation of the geological structure and biological targets on the seafloor. (4) Submariners and scientists can cooperate to synchronize the driving and observation, and perform operation tasks with flexibility and ease on the seafloor. (5) Equipped with advanced terrain and landscape detection devices, manned submersibles can be used for accurate measurements of the environment in unknown areas.

2.1 Structural parameters and performance of manned submersibles

Table 1 lists the structural parameters and equipment performance of major existing manned submersibles (diving deeper than 4 500 m) [7,14], which provides a reference for the development of submersibles with multiple functions in China.

2.2 Core technologies of China's 10 000-meter manned submersible

Since the establishment of the project for full-ocean-depth manned submersible in 2016, the team had made great efforts to achieve major technological breakthroughs for several core components, and the localization rate of core components has exceeded 96.5%. Fendouzhe successfully landed on the bottom of the Mariana Trench at a depth of more than 10 909 m, creating a new record for manned deep-sea submergence in China. The Chinese Academy of Sciences as the national team of science and technology has contributed the greatest part of Chinese wisdom.

(1) New titanium alloy manned ball cabin. The manned cabin of Fendouzhe is spherical and can carry three submariners. The Institute of Metal Research, Chinese Academy of Sciences, together with a number of Chinese enterprises and institutes, performed a series of technical tests, and overcame key technical bottlenecks and difficulties of manned cabin, from drawing design to material selection and development, and to molding and welding.

(2) Precise control system. Shenyang Institute of Automation, Chinese Academy of Sciences worked on the reliable operation of Fendouzhe in the complex environment of abyss, and created an intelligent control system. In addition, a pair of highly flexible and powerful "hands" was developed for Fendouzhe. Using these "hands" on seafloor 10 000 m deep, Fendouzhe completed delicate operations such as capturing rocks and organisms and sampling sediment, demonstrating advanced underwater operability.

(3) "Good sight and sense of hearing"—the underwater acoustic communication system facilitates real-time transmission from 10 000 m deep seafloor. The acoustic system developed mainly by the Institute of Acoustics, Chinese Academy of Sciences realized real-time transmission of text, voice, and images from Fendouzhe 10 000 m deep to the mothership Tan Suo Yi Hao on the sea surface. The acoustic system of Fendouzhe overcame the limitation of full-ocean-depth and achieved complete localization. The high-precision underwater positioning and navigation system integrating acoustic Doppler knotmeter, positioning sonar, and inertial navigation device ensure the continuous cruising and operation of future full-ocean-depth submersibles.

(4) Large buoyancy—Solid buoyancy material ensures the safe return of submersible to surface. Solid buoyant materials [15] are commonly used in deep sea, and the technologies of

Table 1 Comparison of structure parameters and equipment performance of manned submersibles

	Alvin	Nautilus	Shinkai 6500	MIR1/MIR2	Jiaolong	Shenhai Yongshi	Fendouzhe (design parameters)
Country	United States	France	Japan	Russia	China	China	China
Operating organization	Woods Hole Oceanographic Institution	French Research Institute for Exploitation of the Sea	Japan Agency for Marine-Earth Science and Technology	Russian Academy of Sciences	National Deep Sea Center	Institute of Deep-sea Science and Engineering, Chinese Academy of Sciences	Institute of Deep-sea Science and Engineering, Chinese Academy of Sciences
Status	In operation	In operation	In operation	In operation	In operation	In operation	In operation
Year of construction /modification	1964/2013	1984	1989	1987	2009/2019	2017	2020
Maximum dive depth (m)	6000	6000	6500	6000	7000	4500	11000
Number of passengers	3	3	3	3	3	3	3
Total length (m)	7.0	8.0	9.7	7.8	8.2	9.3	10.2
Total height (m)	3.68	3.81	4.1	3.0	3.4	3.9	4.4
Width (m)	2.6	2.7	2.8	3.8	3.0	3.0	3.3
Weight (t)	20.4	19.5	26.7	18.6	22	20	35
Pressure hull material	Titanium alloy	Titanium alloy	Titanium alloy	Nickel steel	Titanium alloy	Titanium alloy	Titanium alloy
Inner diameter of ball cabin (m)	1.98	2.1	2.0	2.1	2.1	2.1	1.8
Diameter of observation window (m)	127（1） 127（2） 280（2）	120（1） 120（2）	120（1） 120（2）	200（1） 120（2）	200（1） 120（2）	200（1） 120（4）	120（3）
Life support time (h)	72	143	128	82	84	82	87
Maximum speed (kn)	3	2.5	2.5	5.0	2.5	2.5	2.5
Payload (kg)	205	200	200	290	220	220	200
Battery/energy (kw·h)	Lithium-ion/115	Lead-acid/50	Silver-zinc/86.4	Nickel-cadmium/100	Silver-zinc/110	Lithium-ion	Lithium-ion
Underwater operation time (h)	4—5	4—5	4	17—20	12	10	10—13
Year of first operation	1964	1985	1989	1987	2008	2017	2020
Dives per year	110—150	100—115	60	20	26	100	—

preparing such materials have long been constrained by a few developed countries. With years of accumulation, the Technical Institute of Physics and Chemistry, Chinese Academy of Sciences took the lead in developing the core raw materials in a short time by using preparation technologies with independent intellectual property rights, which is a breakthrough in the key technologies of buoyancy materials in China. After a series of modification and optimization, a 10 000-m depth solid buoyancy material with high safety was obtained, solving the long-standing technical constrains imposed by foreign countries.

(5) Efficient organization and management—“housekeeper.”

The Institute of Deep-Sea Science and Engineering, Chinese Academy of Sciences, the major designer of Fendouzhe, was responsible for leading the sea tests. To ensure the development of devices for Fendouzhe and passing the sea tests, the institute took the lead in building an ultra-large deep-sea ultra-high pressure test platform to support the timely and successful completion of pressure tests of core large components such as titanium alloy manned ball cabin and solid buoyancy material. The two manned submersible motherships Tan Suo Yi Hao and Tan Suo Er Hao are capable of carrying two manned submersibles in a single trip [16]. They provide stable and reliable support and emergency response from sea surface for the success of submersible sea tests, thus constructing a system for application of technologies and devices.

2.3 Key technologies and development direction of submersibles

Table 2 summarizes the technical development key points and development direction of manned submersibles in China [17].

Based on the current situation of manned submersible development, the construction parameters and performance of submersibles, and the core technologies of 10 000-m depth manned submersibles, the technologies of deep-sea manned submersible developed independently in China are similar to advanced techniques in the world. In virtue of the advantages of deep-sea manned submersible technologies and devices as well as efficient organization and management, we will unravel the mysteries of oceans in the following four aspects.

(1) Research and application of deep-sea organisms and genetic resources. Obtaining sufficient deep-sea biological samples with the use of manned submersible is essential for advanced scientific research. The study of deep-sea organisms is not only of great scientific importance but also has significant practical applications. Since deep-sea organisms are extremely difficult to catch and preserve, the utilization of their genetic resources is particularly important. The study and utilization of genetic resources in extreme deep-sea environments [18] are of great practical significance to reveal the the origin of life, explore the unique life processes and mechanisms underlying the interactions between marine organisms and marine environment, and make full use of these genetic resources in industry, medicine, environmental protection, and military.

(2) Advances into the deep sea and poles. The 18th National Congress of the Communist Party of China suggested building a great maritime country and the 19th National Congress proposed the strategic deployment of coordinating land-sea planning and accelerating the construction of a great maritime country. With the successful tests and acceptance of the 10 000-m manned submersible during the "Thirteenth Five-Year Plan" period, China is capable of entering the deepest ocean in the world for scientific research and operation. The next targets are the polar regions [19], which represent not only an important direction to practice the concept of community with shared future for mankind but also a great endeavor to expand and enhance China's international governance capacity.

Table 2 Technical development key points and development direction of manned submersibles in China [17]

Subsystem	Current technical status	Development direction
Power system	From silver-zinc battery of Jiaolong to lithium-ion battery of Shenhai Yongshi and Fendouzhe, the performance and life cycle of battery have been improved.	● Battery is large and requires miniaturization ● Development of new energy sources with high energy density, high safety, and low environmental impact
Propeller	The technology is mature and meets the needs of current and future submersibles	The main power of propeller comes from electric power supply, and there is no need to improve and develop new propeller
Material and structure	The solid buoyancy material used in the 10 000-m submersible is safe and meets the performance requirements	Meet current and future needs
Navigation and positioning	Navigation and positioning are separate and complicated	Navigation and positioning can be integrated to improve positioning accuracy
Acoustic communication	Complete localization has been achieved	Transformation from digitization to intellectualization
Control system	Mainly manual operation, low level of automation	Improve the automation of control system by referring to unmanned submersibl
Sensor	There are only a few sensors, and the demands should be evaluated based on cross-disciplinary information	● Miniaturization and low power consumption ● Highly integrated sensors ● Organism searching and chemical sensors
Visual imaging	The observation devices are mainly installed in the front for better acoustic and optical detection	Improve resolution, reduce energy consumption, and increase the information storage and transmission speed
Support system on sea surface	The deployment and recovery experience accumulated by Jiaolong basically meets the requirements of submersible operation	Further improvement of supporting devices for joint operation with multiple submersibles
Compatibility of equipped devices	Few spare interfaces and spaces	Spare universal and scalable interfaces with equipment compatibility

(3) Exploration of deep-sea mineral resources. The successful development of the 10 000-m manned submersible has greatly improved the ability of deep-sea resource exploration of China [20]. The high pressure and darkness in deep sea limit the accessibility of regular scientific research equipment. This can be solved by the use of full-ocean-depth manned submersible, which can carry scientists, engineers, and various detection devices, and quickly and accurately reach deep-sea complex environments for delicate fixed-point operation. Efficient resource exploration, scientific expedition, and offshore seafloor operation can then be achieved. The full-ocean-depth manned submersible represents an important technical means for peaceful development and utilization of deep-sea resources.

(4) Establishment of a comprehensive big data system for oceans. The oceans occupy approximately 71% of the Earth's surface, and the world has entered the era of marine big data in the 21st century. There are numerous marine observation and investigation methods, such as near-shore mapping, visual monitoring of islands, detection of marine fishery resources, marine buoy monitoring, marine scientific expedition, offshore environmental monitoring around oil and gas installations, and satellite remote sensing. Tremendous marine observation and monitoring systems have been established, and a huge amount of data has been collected for marine science. The exploration of deep sea with manned submersible will supplement the deep-sea biological and mineral resource data to the marine big data.

3 Suggestions for the development of manned submersible in China

The ocean is not only the cradle of life, but also the treasure house of resources, the artery of water transportation, and the key area of implementing strategies to build a great country [21]. The 18 000 km of mainland coastline and 14 000 km of island coastline mark the vast maritime boundary of China. The goal of building a great maritime country was proposed in the report of the 18th National Congress of the Communist Party of China, which was proposed for the first time in the history of the development of the Chinese nation. This goal is important for the perpetual development of the Chinese nation, China's progress toward prosperity and strength, and the peace and development of the world. In the report of the 19th National Congress of the Communist Party of China, it was proposed again that we should adhere to coordinated land-sea planning and accelerate the construction of a great maritime country and that building a great maritime country is an important part of the socialism with Chinese characteristics.

On June 12, 2018, General Secretary Xi Jinping said during a visit to Shandong Province: "I have always had a belief in building a great maritime country. The development of marine economy and marine science is critical to our strategies for becoming a great country, which must be well managed. The key technologies must be developed independently, and marine economy has a bright future." The development of marine economy and science requires deep-sea scientific expedition and manned submersibles. Standing at a new historical starting point, how to develop manned submersibles for deep-sea scientific expedition and marine resource exploitation? Under the new historical conditions and in combination with the existing achievements, we should follow the rules of scientific development, speed up transformation of research achievements, and expand the scope of comprehensive application.

(1) Establishing medium- and long-term goals for deep-sea scientific expedition and marine resource exploitation. Leveraging the advantages of the three manned submersibles, we should develop systematic plans and create a diversified mechanism for stratified management at different depths from offshore to the open sea [22]. It is necessary to promote the development of serial full-ocean-depth submersibles with multiple functions. Submersibles with different diving depths can be used at different periods and stages for different tasks to support the investigation of seafloor resources, marine geology, deep-sea genetic resources, as well as scientific research, underwater engineering, salvage and rescue, and deep-sea archaeology.

(2) Accelerating the transformation of research achievements. Owing to the development in basic research, the localization rate of core components of Fendouzhe exceeds 96.5%. To take better and greater advantages of basic studies, we shall promote the transformation of research achievements and the development of civil submersible devices. Social investment should be encouraged to support the study of the ocean and establish diversified outputs of research achievements. The available research achievements should be shifted from digital to intelligent application.

(3) Building a platform for open and collaborative data sharing. We should establish a data sharing platform for management of the acquired scientific samples and documents. The exploitation of deep-sea resources, the effective use of scientific research facilities, and the sharing of data should be integrated for guiding the coordinated innovation and development of sectors, regions, and industries. We should also provide channels for efficient exploitation and utilization of marine resources, guide the participation of universities and research institutions, and promote the collaboration of industries, universities, and research institutions, thus building a new development mode featuring cooperation of multiple sectors.

(4) Rationally exploiting and protecting marine resources. The purpose of deep-sea scientific expedition is to address major scientific issues such as the origin of life and the evolution of the Earth. We should attach great attention to the protection of marine environment [23] and resources, properly explore and effectively utilize the ocean, and promote the transformation toward recycling and sustainable marine exploitation.

(5) Maintaining the high investment in basic research and innovation. Although the localization rate of core components has been significantly increased, it should be noted that there is still a large gap between the performance of China's manned submersible and international top-level submersibles. We should optimize the technical parameters and performance of submersible devices on the basis of existing technologies. It is also suggested to strengthen the research and development of non-core components to overcome technological constraints.

(6) Improving the supporting facilities of scientific exploitation ships. The existing motherships are well equipped, whereas the submersibles are highly dependent on the hardware of the mothership. According to the medium- and long-term objectives of deep-sea scientific exploitation, the switchability of scientific exploitation ships and the compatibility of hardware should be improved in a staged manner, and the supporting facilities should be continuously updated.

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