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China's first deep manned submersible, JIAOLONG

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A deep manned submersible is indispensable to deep ocean exploration. No other equipment can bring scientists to extreme sea floor depths to do research *in situ*. Marine geology, seafloor geophysics, marine biology, and oceanic chemistry are the fields that scientists are particularly eager to study [1–6]. Chinese scientists have long dreamed of using their own submersible to probe the deep sea. China's recent fast development of a deep manned submersible has realized that dream.

A project, "Development of a Manned Deep Submersible", now named JIAOLONG, was formally started in 2003. After different stages of conceptual design, preliminary design, detailed design, construction, assembly, and open water tank test, the sea trials were conducted at depth of 1000 m in 2009 and 3000 m in 2010.

1 Mission, design and specifications

The main mission of the submersible is to carry scientists, engineers and their various instruments to the rugged deep sea topography to perform tasks of oceanic geology, geophysics, biology, and chemistry in operational modes of constant height cruising above the sea bottom, hovering at a designated position in mid-water, or resting on the sea bottom.

The submersible may conduct many kinds of tasks. Some of them are: (1) to take samples of the deposits, swimming creatures at a required location; (2) to take core samples by means of a mini-drill in areas of cobalt-rich crust; (3) to measure the temperature and take water samples at the center of an active hydrothermal vent or any designated target; (4) to make high resolution topographic and geomorphological maps with a bathymetric side-scan sonar, with the submersible tracing the topography and cruising at a constant height above the bottom; (5) to take pictures and make videos of specific targets, such as marine wrecks; and (6) to deploy or recover devices in a specific location or to inspect and maintain marine structures such as pipelines and cables.

Main design considerations: (1) Cost effective principle: to obtain as much data and as many samples as possible and let as many scientists as possible participate in the deep dives. (2) Environmentally friendly principle: to cruise as quietly as possible in the water and to throw as less contaminated drops as possible to the seabed. (3) Convenient and easy to assemble and maintain principle. (4) Ergonomics principle: to provide a comprehensive solution to its operation and observation capabilities in a manner as relaxing as possible so as to minimize fatigue for the pilot and scientists during their long working hours in the submersible at great depths. (5) Sea states: to be able to launch under sea state 4 and recover under sea state 5.

Many contributions were made by the Chinese engineers and scientists from all related fields in order to fulfill the mission, the tasks, and the design principles. The molded lines, resistance analysis, hydrodynamic layout, maneuverability, descending and ascending tests without power supply, etc. were carried out during different stages of the conceptual design, preliminary design, and detailed design to ensure the maneuverability of the submersible. JIAOLONG's general arrangement had properly assigned responsibilities for all the functions and equipment, coordinating the conflicts, interfaces and compatibility issues, and preventing the participants from disturbing each other in the process (Figure 1).

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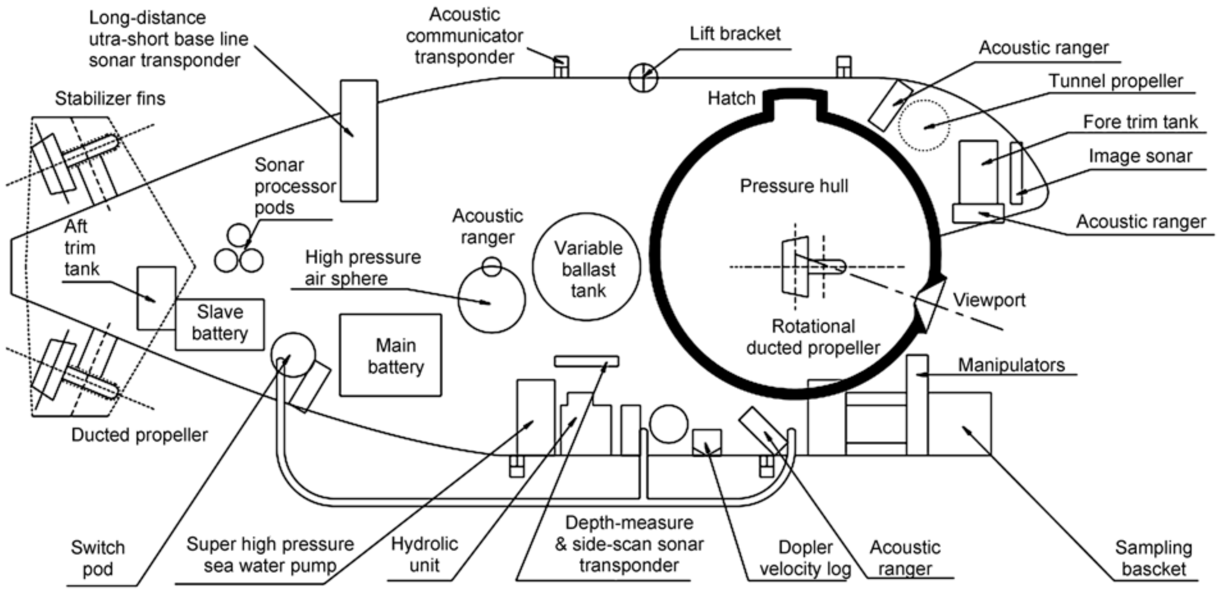

Figure 1 JIAOLONG's configuration.

The submersible looks like a shark. Its stabilizer fins are arranged in the form of an X. The thrusters are distributed as vectors in different directions. Four ducted propellers are the main thrusters, which are arranged as a cruciform in the stern. There is a channel thruster in the bow and one rotational ducted propeller on each broadside in the middle of the vehicle. With the control system in operation, the vehicle has the capability of space motion with six degrees of freedom. To save energy, the descent and ascent procedure is designed to operate without any power supplies.

The main spherical pressure hull (Φ2100 mm) is made of 12 separate side sections (lobes) and 2 bottom sections of spherical shape. The side and bottom sections were forged from flat plate blanks of a specially chosen configuration. The welded hemispheres were placed into a special oven for thermal treatment to relieve residual stresses and eliminate distortions due to the machining of the hemispheres. Manual TIG welding was used. Inspection was conducted after each weld procedure using three methods, i.e., fluid penetration, X-ray, and ultrasonic, to detect any disfigurement.

The conical hatch and window designs were one of the key technologies for manned pressure hull design. The optimized geometrical dimensions of the hatch coaming made the hatch deform compatibly with the cover under work pressure to keep the access hatch cover well sealed. Peak bending stresses were avoided. This problem was solved through repetitive finite element analyses.

Three types of hydrostatic pressure te sts were carried out to examine the fabricated manned pressure hull performance. They were: (1) Cyclic testing under pressures increasing from 0 to 71 MPa and then decreasing from 71 MPa to 0 over 6 cycles. (2) Hydrostatic testing under a test pressure of P_{test}=78 MPa with one hour exposure. This test was to check the structural strength and sealing abilities in 1.1 times the service pressure. (3) Long-term hydrostatic test under service pressure of P_w=71 MPa with eight hours exposure. In this test, the pressure increasing and decreasing rates were equal to the actual submersible descending and ascending speed. The exposure time under 71 MPa pressure was equal to the submersible's working time at the sea bottom. The stress distribution and the windows creep speed indicated the actual working conditions. All the test results mentioned above indicated that the stress distributions were in good agreement with the design calculations. The sealing ability was very good. No plastic deformation was found.

The main framework is a welded titanium space frame structure. The framework was tested with twice the equivalent actual load distributions. The test was to simulate the recovery working conditions. The test results indicated that the stress distributions were also in good agreement with the design calculation results.

JIAOLONG's communication system consists of two parts, the surface and underwater components. The submersible communicates with its support ship by VHF radio before diving or after surfacing, and communicates with the ship by acoustically transferring audio, image, and text information when it is submerged.

There are two major methods for navigating the submersible. Under normal conditions, the navigation depends on an ultra-short baseline acoustic array mounted on the support ship and a transponder on the submersible. The position of the submersible relative to the ship is calculated using the distance between the sonar array and the transponder. Consequently, the submersible's geographic position is calculated with the relative position and the information from the DGPS on the support ship, which is then transferred to the submersible acoustically.

The second method, called a "combined navigation system", relies on the submersible's calculations. It can estimate the submersible's position relative to a given starting point by time intervals according to the information from the motion sensors, Doppler sonar, fiber gyroscope, and depth sensor. The combined navigation system will be used whenever there is a breakdown in the ultra-short baseline sonar or acoustic communication system.

There are two cruising modes, manual and automatic control. In the automatic control mode, the submersible can keep a constant heading, and depth (or height), and/or hover in a designated position, which greatly improves the navigation capability of the submersible and lightens the pilot's burden.

The submersible is equipped with various types of detecting equipment. Eight lights, quartz halogen, HID or HMI are mounted. Video and still cameras are distributed around the submersible to take video movies and photographs. The imaging sonar has a maximum extension of 200 m, and seven ranging sonars are also mounted on the submersible to detect barriers. Doppler sonar is used to measure the current velocity. The bathymetric side-scan sonar can detect a variety of small objects with different landforms. Two 7-function manipulators are mounted on the submersible to deploy and recover devices. A sediment sampler, pressure-sustained liquid sampler and rock corer are alternative devices for the submersible when necessary.

Safety is the most important consideration. Besides normal ballast shedding, the manipulator hydraulic hoses, power battery wires and their fixed bolts can be cut or exploded off in the situation where the submersible becomes entangled on the bottom, to release the submersible and ensure the crews' safety and protect the main equipment. Comprehensive tests were conducted before the sea trials and all the mechanism functioned well [7, 8].

JIAOLONG has a very comparable specification with the world's existing submersibles of its type. A summary of the specifications is given in Table 1.

Table 1 JIAOLONG's specifications

Parameters	Specifications
Max operational depth (m)	7000
Dimension	8.3 m×3.0 m×3.2 m
Pressure hull	Φ2.10 m (inner)
Material	Titanium alloy
Weight in air (t)	22
Launch & recovery	Single point lifting bracket
Crew	1 pilot, 2 scientists
Life supporting time	12 hours (normal operation), 72 hours (emergency)
Payload (kg)	220
Power supply	Oil filled sliver & zinc battery >110 kWh
Underwater time	12 hours
Speed	Cruise: 1 knot; max: 2.5 knots
Navigation system	USBL; laser gyro
Control mode	Manual & automatic
Dynamic positioning	Hovering ability at a position
Communication	VHF radio; underwater telephone; acoustic communicator×2
Manipulator	Servo: with 7 functions; on-off: with 7 functions
Lights	HMI×2; HID×2; Quartz halogen×4
TV camera	3CCD×1; 1CCD×2
Still camera	Camera×1
Acoustic observation	Imaging sonar; bathymetric side-scan sonar: 2×200 m coverage
Obstacle avoiding	7 ranging sonar
Tool	Sediment sampler: volume 1 liter Rock drill: Φ50 mm × 200 mm corer Fluid sampler: 500 mL with pressure preserved

2 Open water tank tests and sea trials

Various tests were conducted such as the lift supporting system performance test, emergency jettison mechanism test, anti-collision sonar performance test, and braking distance measurement test at a speed of 1 knot. Before the sea trials, nearly 100 rigorous dives were carried out at the China Ship Scientific Research Center (CSSRC), in an open water tank shaped like a bowl, with a diameter of 85 m and a maximum depth of 15 m. For each test, the preparation, test process and maintenance were done strictly in compliance with the simulated sea trial procedures [9].

A typical operational procedure for a dive is divided into eight steps: preparation, launching, descending, cruising, task taking, ascending, recovery and maintenance. Each step is broken down into smaller operations. All sea trial participants have a flow chart of all the operations to ensure everyone knows what to do immediately and subsequently, thus making the sea trial safer. Assuming a 7000 m dive is planned, a typical procedure will last for 12 hours, consisting of 0.5 hour each for launching and recovery, 2.5 hours each for descending and ascending and 6 hours for sea bottom work. Naturally the duration of the descending and ascending times varies depending on the depth of water. For example, if the test is in shallower water, the descending and ascending times will be shorter, and therefore the task-taking time may last longer. A normal dive procedure usually begins in the morning and ends in the evening before dark.

The first set of sea trials was from August 6 to October 19, 2009. During this period, 50 m, 300 m and 1000 m depth tests were carried out and 20 dives were made in South China Sea. The deepest dive, the 20th dive, reached 1109 m on October 3.

This year's 49 day trial, from May 31 to July 18, was carried out in South China Sea. JIAOLONG, with three crew members onboard, completed 17 dives, bringing the total number of trial dives to 37. Among these dives, four dives exceeded 3000 m with the deepest reaching 3759 m in depth, and the longest submerged time was 9 hours and 3 minutes, both setting the record for a Chinese manned submersible.

JIAOLONG landed many times on the seafloor, including "frog jumps" in the dive to make soft landings and use the manipulators mounted on the submersible to plant the Chinese national flag, to sample the deep water, and to deploy a memorial mark, called the "Dragon's Palace", depicting a historical legend on the seabed. The submersible took many pictures and made several hours of videos of the organisms living near the bottom. Two sea cucumbers were captured in the sample basket in a dive, the larger being 250 mm long.

The submersible's maneuverability and automatic control capabilities such as constant depth, heading and height keeping were tested during the trials (Figure 2).

XIANGYANGHONG 09, transferred from a geological research vessel, was JIAOLONG's mother ship in the trials. Since the ship was built 30 years ago and was quite noisy, the acoustic communication distance and quality was affected to some extent during the trials. The sea trial team had a great difficulty with these problems. The captain had to sail with one engine turned off to enable communication of instructions, data, and images between the mother ship and JIAOLONG.

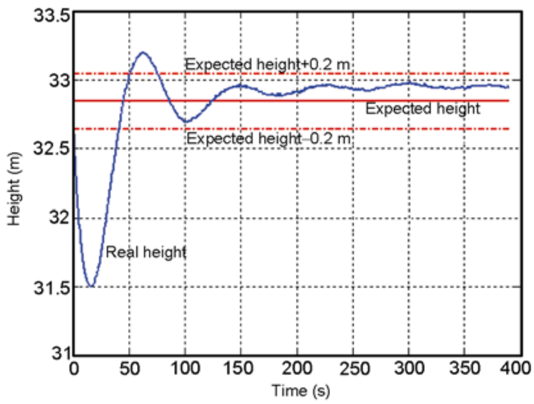

Figure 2 Automatic height keeping.

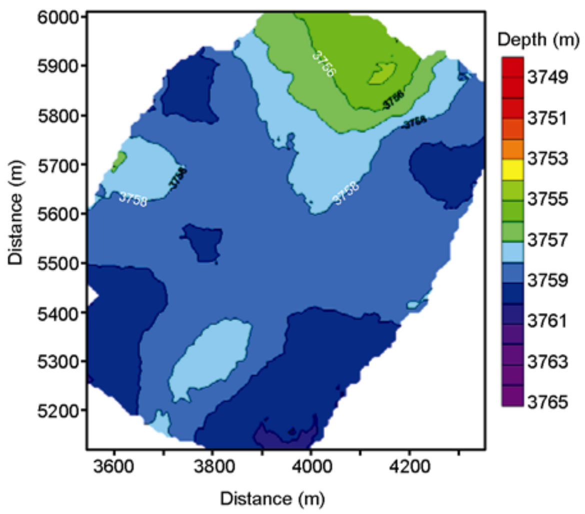

Figure 3 Seafloor mapping.

High resolution maps of the sea bottom's topography in the designated areas were plotted with the bathymetric side-scanning sonar (Figure 3). Data and images were transmitted from JIAOLONG to XIANGYANGHONG 09, so that all the information, including all life-support parameters of the hull, energy consumed, CTD, direction and velocity, pitch and roll angle, and other important status information of the submersible, could be clearly shown on the monitoring screen in the mother ship.

3 Summary

JIAOLONG's function and capability were fully tested during its 37 dives. The longest underwater time was 543 minutes, and the deepest dive of 3759 m was made on its 37th dive. The Chinese national flags and memorial "Dragon Palaces" were placed on the seafloor. 525 mL of pressure-sustained seawater and two sea cucumbers were sampled. Test results have indicated that all the functions and capabilities were in good agreement with the design data.

This paper is a team effort, not only of the authors but also of all participants in the project. First and foremost, we would like to show our gratitude to Professors Xu Qinan, Wu Chongjian, Hu Zhen, Liu Tao, Wang Xiaohui, and Zhu Min, who have contributed greatly to the development of JIAOLONG and its sea trials. We extend our thanks to JIAOLONG's pilots, especially Mr. Ye Cong, who, as the chief pilot, dove with JIAOLONG many times during the sea trials. We also sincerely express our thanks to the Ministry of Science and Technology and the State Oceanic Administration of China, the funding supplier and organizer of the project, and all the institutions involved in JIAOLONG's development and its sea trials.

1 Nanba N, Morihana H, Nakamura E, et al. Development of deep submergence research vehicle "SHINKAI 6500". Techn Rev Mitsubish Heavy Industr Ltd, 1990, 27: 157–168
2 Momma H. Deep ocean technology at JAMSTEC. Mar Technol Soc J, 1999, 33: 49–64
3 Vadim V K, Jury K M. About designing experience of submarines and deep submersibles from titanium alloys in bureau "MALACHITE". Titanium'99, 1999. 1125
4 Sagalevitch A M. Experience of the use of manned submersibles in P. P. Shirshov Institute of Oceanology of the Russian Academy of Sciences. In: Proceeding of the 1998 International Symposium on Under-water Technology, 1998. 403
5 Kohnen W. Manned research submersibles: State of technology 2004/2005. MTS J, 2005, 39: 122–127
6 http://www.unols.org/meetings/2006/200605des/200605desmi.html
7 Cui W C, Xu Q N, Liu T, et al. Introduction to the development of a 7000 m manned submersible. The Post-Symposium Workshop of Underwater Technology 2007, April 23–24, 2007, hosted by Shanghai Jiao Tong University and China Ship Scientific Research Center. 2007
8 Cui W C, Xu Q N, Liu T, et al. Design and construction of the deep manned submersible "Harmony" (in Chinese). J Ship Sci Technol, 2008, 30: 17–25
9 Hu Z, Wang X H, Zhu M, et al. Tank test of the deep manned submersible "Harmony" (in Chinese). In: The Third Asia-Pacific Diving & Underwater Technology Conference, 14–15 June, 2008, Shanghai, China