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Development Status and Prospects of Deep-Sea Technology Equipment: Postprint

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Abstract

After nearly half a century of concerted efforts, China has achieved considerable progress and development in marine technology and equipment, with recent advancements in deep-sea technology and equipment providing new impetus for innovation in marine science. The Strategic Priority Research Program of the Chinese Academy of Sciences, "Material and Energy Exchange in Tropical Western Pacific Ocean Systems and Its Impact," guided by scientific demands, tracking international frontiers, and based on the current development status of China' s deep-sea technology and equipment, proposed the development of deep-sea detection and operation equipment with clearly defined scientific application objectives and the formation of a capability to conduct comprehensive marine detection and operations utilizing autonomous observation systems, continuous observation and operation systems, and new types of marine sensors and sampling equipment. Over the 4-year implementation period of the program, the deep-sea technology and equipment, oriented toward the scientific objectives of the program, formed technical equipment with completely independent intellectual property rights, produced a number of influential achievements, provided advanced technical means for marine scientific research, promoted the development of China' s deep-sea detection and operation technology, and played an important pioneering role in the development of China' s deep-sea technology and equipment.

Full Text

Preamble

Special Topic: Current Status and Future Prospects of Marine Science
Review and Prospect for Chinese Deep-sea Technology and Equipment

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Abstract

After nearly half a century of dedicated effort, China has achieved remarkable progress in marine technology and equipment. In recent years, the development of deep-sea technology and equipment has provided new momentum for innovation in marine science. The Chinese Academy of Sciences' Strategic Priority Program "Western Pacific Ocean System: Structure, Dynamics and Consequences" (WPOS) takes scientific requirements as its guide, tracks international frontiers, and builds upon the current state of China' s deep-sea technology development to propose the development of deep-sea detection and operational equipment with clearly defined scientific applications. The program aims to establish comprehensive capabilities for ocean exploration and operations using autonomous observation systems, continuous observation and operation platforms, and novel marine sensors and sampling devices. Over its four-year implementation period, the deep-sea technology and equipment developed for the program' s scientific objectives have yielded fully independent intellectual property rights, produced influential achievements, provided advanced technical means for marine scientific research, promoted the development of China' s deep-sea exploration and operation capabilities, and played a significant pioneering role in the nation' s deep-sea technology and equipment development.

Keywords: deep-sea technology and equipment, autonomous observation, continuous observation and operation, new ocean observing sensors and sampling systems

Introduction

Marine science is the source of marine technology development, while marine technology drives innovation in marine science. Historically, innovations in oceanography and discoveries of new marine resources have originated from ocean survey and observation results, demonstrating that innovative marine science research is inseparable from marine observation and detection technology. Within the CAS Strategic Priority Program "Western Pacific Ocean System: Structure, Dynamics and Consequences," the project "Deep-sea Equipment Development and Application" was established to address marine scientific issues such as air-sea interactions in the tropical western Pacific and the influence of the Kuroshio Current on China' s coastal waters. The research objective is to track international frontiers and independently develop a series of marine technologies and equipment with world-class capabilities, providing the program with autonomous observation systems, continuous observation and operation platforms, new sensors, and detection and sampling devices required for marine scientific research. This effort provides technical means for solving and scientifically analyzing marine scientific problems and phenomena, generates equipment with independent intellectual property rights, and promotes the development of China' s deep-sea exploration and operation technology.

1. Project Research Content

To meet the program's scientific requirements, the project focused on developing and applying three categories of marine technology equipment.

1.1 Autonomous Observation Systems

Autonomous observation systems operate independently after deployment from the mother ship, primarily utilizing relatively long-term, continuous autonomous mobile observation platforms to meet marine scientific survey requirements for high spatiotemporal resolution field observation data or autonomous observation in sensitive areas. These systems mainly include 300 m/1,000 m underwater glider autonomous observation systems, 1,000 m-class long-term fixed-point profile observation autonomous underwater vehicles (AUVs), and 4,500 m-class deep-sea hydrothermal detection AUVs.

The underwater glider is a novel underwater observation platform that combines buoy, subsurface buoy, and underwater robot technologies. By adjusting its buoyancy to provide driving force and relying on the lift from horizontal wings to convert vertical motion into horizontal motion, while controlling its attitude and heading through built-in control systems, the glider achieves continuous, controllable gliding motion to meet the program' s requirements for high spatiotemporal resolution data or autonomous observation in sensitive areas. The underwater glider autonomous observation system utilizes multiple gliders working in coordination to complete observation tasks.

The long-term fixed-point profile observation AUV is a novel system combining self-propelled and vertical profile motion capabilities. Through high-precision bidirectional buoyancy regulation technology, it achieves optimal horizontal navigation and vertical profile movement, carrying relevant sensors to obtain over 30 days of long-term profile data on ocean parameters including currents, dissolved oxygen, turbidity, chlorophyll, temperature, salinity, and depth, meeting the need for long-term, fixed-point, continuous observation in sensitive areas traversed by the Kuroshio Current.

The deep-sea hydrothermal detection AUV system is a 4,500 m-class AUV integrating micro-topography measurement, seafloor photography, and hydrothermal anomaly detection sensors. It can autonomously navigate in complex near-seafloor environments to meet the requirements for fine acoustic detection and near-bottom optical observation in deep-sea hydrothermal activity areas and cold seep regions.

1.2 Marine Continuous Observation and Operation Systems

Marine continuous observation and operation systems primarily rely on mother ships to address urgent needs in research on ocean material, energy, and heat transport processes, promoting studies on ocean circulation dynamics in the western Pacific and China' s coastal waters. The main components include a 500 m ship-towed fiber optic temperature-depth profile continuous observation system, a 3,000 m deep-sea ecological process long-term fixed-point observation system, and a 6,000 m-class scientific research remotely operated vehicle (ROV) system.

The ship-towed fiber optic temperature-depth profile continuous measurement system is a high-density, high-efficiency ship-towed measurement equipment that fully leverages its advantages in continuous temporal and spatial measurements, providing a new technical means for ocean surveys and scientific research to rapidly and efficiently obtain high spatiotemporal density temperature-depth data.

The deep-sea ecological process long-term fixed-point observation system is a frame-type underwater fixed observation platform that can carry different sensors according to scientific requirements, conduct long-term continuous fixed-point observations on the seafloor, and adjust observation positions through ROV assistance. It can obtain synchronized multi-sensor fixed-point observation data for over one year to study the formation and evolution mechanisms of deep-sea ecosystems, biological growth cycles and metabolic rhythms, and seasonal population changes.

The deep-sea scientific research ROV system will be China' s first independently developed 6,000 m-class ROV for scientific applications, employing all-electric propulsion technology to reduce platform noise and environmental impact. Using fiber optic communication technology for real-time video and data transmission, advanced lighting and camera equipment enable broadcast-quality underwater high-definition video filming. With high-precision navigation and positioning systems, it achieves high-precision multi-degree-of-freedom underwater control, features rich equipment interfaces, can carry multiple scientific instruments, and is equipped with two dexterous manipulators for near-seafloor sampling operations.

1.3 New Marine Observation Sensors and Sampling Systems

New marine observation sensors and sampling systems operate based on mother ships or underwater platforms. By developing deep-sea biological and ecological environment detection technologies and sensors, as well as deep-sea hydrothermal detection technologies and sensors, the project addresses the lack of effective sensors and systematic detection technologies for deep-sea environments, improving deep-sea observation and detection capabilities and promoting research on deep-sea biogeochemical cycles. The main components include a 4,500 m-class Raman spectroscopy in-situ quantitative detection system based on deep-sea ROV platforms, 3,000 m/6,000 m deep-water visual controllable lightweight sediment coring systems, a 3,000 m high-flux deep-sea water sampling and fractional filtration system, and a 4,500 m-class high-precision temperature chain for deep-sea extreme environments.

The Raman spectroscopy in-situ quantitative detection system based on deep-sea ROV platforms utilizes Raman spectroscopy' s advantages of non-contact, non-destructive, and multi-component simultaneous detection. The RiP system developed based on Raman spectroscopy technology is particularly suitable for in-situ material composition detection and analysis in extreme environments such as deep-sea hydrothermal vents and cold seeps.

The deep-water visual controllable lightweight sediment coring system combines reciprocating pneumatic tamping key technology, uses vertical sampling system deployment and recovery operations, and adds real-time control and monitoring and underwater positioning functions for comprehensive sediment column collection in deep water.

The high-flux deep-sea water sampling and fractional filtration system employs in-situ filtration to obtain samples, providing a simple and effective sampling technical method for studying deep-sea suspended particulate matter and changing the traditional work mode of using water samplers and conducting filtration in onboard laboratories.

The high-precision temperature chain for deep-sea extreme environments conducts precise gradient measurements of temperatures at hydrothermal vents and cold seep areas to study deep-sea heat transport processes.

2. Project Progress

After four years of development work, the three types of deep-sea technology equipment have completed design, processing, manufacturing, debugging, and lake/sea trial phases, fully meeting main technical specifications. Closely integrated with scientific questions, some equipment has already played important roles in sea trials and expedition applications, achieving significant scientific results.

2.1 Preliminary Establishment of China' s Autonomous Observation System for Marine Scientific Research

The project developed a series of autonomous observation systems for marine scientific research, establishing a technical system for China' s autonomous observation capabilities and forming continuous observation capabilities for ocean environments above 1,000 m and fine near-seafloor detection capabilities above

4,500 m. The continuous observation time for ocean environments exceeded one month, with voyage distances surpassing 1,000 km, laying a technical foundation for long-term, large-scale ocean observation. The project pioneered the use of large-depth AUVs for fine acoustic and optical detection near the seafloor to conduct cold seep research in China.

2.1.1 Underwater Glider Autonomous Observation System The "Sea Wing" 300 m and 1,000 m series underwater gliders were developed by the Shenyang Institute of Automation, Chinese Academy of Sciences. During development, a series of sea trials were conducted in conjunction with scientific objectives, improving the technology maturity of underwater gliders and leading China' s underwater gliders into practical observation applications. The communication status of the underwater glider on the water surface and its mesoscale eddy observation path are shown in [Figure 1: see original paper].

In October 2014, the "Sea Wing" underwater glider completed a sea trial in the South China Sea lasting over one month. During the long-voyage test, the glider continuously navigated within a 55 km × 55 km area, achieving a breakthrough voyage distance of 1,022.5 km and obtaining 229 profiles of 1,000 m depth observation data. This marked the first time a Chinese underwater glider' s continuous observation voyage exceeded 1,000 km, with continuous observation time reaching 30 days. Data processing revealed two occurrences of upper ocean mixed layer cooling in the test area, and the glider' s high-precision data provided strong support for quantitative analysis of the cooling causes.

In July 2016, three underwater gliders conducted a mesoscale eddy observation experiment in the sea area east of the Xisha Islands in the South China Sea. Combined with remote sensing satellite data and drifting buoy data, different observation strategies were employed to conduct 15 days of continuous observation of a 100 km diameter mesoscale eddy east of the Xisha Islands. For the first time in China, three underwater gliders were used for multi-parameter continuous observation of a dynamic maritime target, accumulating a total voyage distance of 1,033 km and successfully completing 316 profiles of 1,000 m depth, validating online control strategies for tracking dynamic targets combined with satellite remote sensing data and laying a technical foundation for networked observation applications of underwater gliders.

In early June 2016, the "Explorer 1000" successfully completed a 20-day large-depth sea trial in the South China Sea, verifying the practicality of its deployment and recovery operations and successfully completing safe recovery work under sea state conditions above level 5. The system validated the reliability of its autonomous navigation and diving/floating functions in deep-sea operations, with maximum dive profiles reaching 700 m. In comprehensive tests, the "Explorer 1000" continuously operated underwater for 7 days, traveling over 500 km and completing 43 continuous dive profiles, with maximum working depth exceeding 800 m, reaching international advanced levels.

In July 2016, the "Explorer 1000" completed 11 underwater navigation tests in the sea area east of the Xisha Islands, accumulating over 100 hours of operation and 400 km of voyage distance. The maximum continuous mission time for a single task was 94 hours, with a maximum voyage distance of 364 km, completing 25 continuous observation profiles and obtaining 30 hours of continuous profile observation data on currents, temperature-salinity-depth, chlorophyll, and dissolved oxygen in the Zhangzi Island sea area, validating the semi-diurnal tide phenomenon in this region.

2.1.2 Long-term Fixed-point Profile Observation AUV System The long-term fixed-point profile observation AUV system ("Explorer 1000") is a completely new technology equipment developed by the Shenyang Institute of Automation based on scientific questions proposed by the program. It fully integrates AUV and underwater glider technologies, breaking through key technologies including high-precision bidirectional large-depth buoyancy regulation and long-endurance multimodal control. The "Explorer 1000" features autonomous navigation, powerless diving/floating, and supervisory sleep modes, representing a domestic innovation and reaching international advanced levels. The "Explorer 1000" AUV is shown in [Figure 2: see original paper].

2.1.3 Deep-sea Hydrothermal Detection AUV System The deep-sea hydrothermal detection AUV system ("Explorer 4500") was jointly developed by the Shenyang Institute of Automation and the Institute of Oceanology. It is a 4,500 m-class AUV system integrating micro-topography measurement, seafloor photography, and hydrothermal anomaly detection sensors ([Figure 3: see original paper]). During development, the project pioneered the integration of ultra-short baseline positioning information into combined navigation technology in China, developing proprietary combined navigation and data processing software that improved work efficiency and large-area detection capabilities. The system also broke through autonomous collision avoidance technology based on forward-looking sonar information, enhancing its ability to adapt to complex environments and ensuring safe near-seafloor navigation.

During testing, the system used ultra-short baseline positioning as the standard. Error curves show the eastward and northward errors of the self-developed navigation system and PHINS navigation over time. PHINS position errors reached maximum values of 50 m eastward and 70 m northward, while the self-developed navigation system's errors were within 20 m in both directions, essentially equivalent to ultra-short baseline positioning accuracy. High-precision navigation and positioning data provide strong technical support for near-seafloor detection.

From July 22, 2016, the "Explorer 4500" successfully completed 16 days of sea trials and experimental applications in cold seep areas, conducting 8 continuous dives. For the first time in China, a deep-sea AUV successfully used ultra-short baseline positioning mode for detection operations, obtaining large-area fine topographic maps of cold seep areas and thousands of high-definition seafloor images. This marked China' s first fine topographic and substrate detection, near-bottom photography, and multi-parameter physicochemical environment detection of cold seep areas by a deep-sea AUV, yielding substantial scientific data.

2.2 Preliminary Establishment of China' s Most Advanced Marine Continuous Observation and Operation System

The project developed ship-based large-area continuous observation, seafloor fixed-point long-term observation, and large-depth operation systems, forming marine continuous observation and large-depth operation capabilities and establishing China' s most advanced marine continuous observation and operation system for sea trials and expedition applications.

The ship-towed fiber optic temperature-depth profile continuous measurement system was developed by the Institute of Semiconductors, Chinese Academy of Sciences. Key breakthroughs included arbitrary-length splicing and chain formation, and low-loss, crush-resistant fusion splice protection technology. The project successfully developed 50 m and 200 m temperature-depth measurement chains, completed technical 攻关 on sensor design and packaging, demodulator long-term stability, and winch system design and integration, and conducted corresponding sea trials. A 500 m towed chain system is under preparation.

In July 2016, towing sea trials were conducted in the North Yellow Sea. The winch and guide pulley are shown in [Figure 4: see original paper]. The sea trial data obtained by the temperature chain tow provided very high precision and spatial resolution observations of the cold water mass, providing important support for traditional oceanographic surveys. The data not only enriched existing survey methods but also provided high-quality data for scientists analyzing ocean phenomena, further promoting ocean survey and research development.

The Yellow Sea cold water mass reaches its peak in summer, with a wide distribution range showing a triangular pattern. Its core is located around 38.5°N. The experimental data show that isotherms at the thermocline are inclined, with the southern thermocline position shallower than the northern position, and southern thermocline isotherms denser than northern ones, with an 8°C closed cold water core at the bottom.

2.2.2 Deep-sea Ecological Process Long-term Fixed-point Observation System The deep-sea ecological process long-term fixed-point observation system (lander) was developed by the Shenyang Institute of Automation ([Figure 5: see original paper]). After completing 3,000 m sea trials in the South China Sea in April 2016, the lander conducted 16 days of continuous underwater observation in a cold seep area of the South China Sea aboard the R/V "Science" in June 2016. With ROV assistance, the observation point position was precisely adjusted, obtaining high-definition photos of cold seep organisms and large amounts of observation data on seafloor physical and chemical environmental parameters. This provided strong data support for scientists studying whether changes in biological communities and their environmental characteristics in South China Sea cold seep areas show tidal cycle correlations.

Through experimental scientific applications, the lander obtained in-situ physicochemical environmental parameter data from dense cold seep biological communities. Contrary to the general belief that deep-sea environments are hypoxic, the lander' s observations showed that dissolved oxygen saturation in this area approached 50%, not creating stress for most benthic shellfish. According to ADCP analysis, bottom currents in this cold seep area are very strong, and Kuroshio bottom water may be transported to the cold seep area through this current, timely replenishing DO consumption by bottom organisms. Methane concentration showed obvious diurnal variations, with tides likely being the main cause. Methane concentration changes significantly affect biological behavior. During periods of high methane concentration, the deep-sea mussel *Bathymodiolus* increased its shell-opening and water-exchange frequency, while the alvinocaridid shrimp also showed migration characteristics following high CH value areas. These results indicate that methane concentration is one of the main factors affecting deep-sea biological behavior, and that deep-sea bottom currents and tides also provide favorable habitats for deep-sea organisms and affect population transport.

2.3 Development of Internationally and Domestically Leading New Marine Observation Sensors and Sampling Systems

The project developed new sensors, detection, and sampling equipment, forming large-depth, high-precision in-situ fine detection and sampling capabilities, with some achievements reaching international leading levels.

2.3.1 Raman Spectroscopy In-situ Quantitative Detection System Based on Deep-sea ROV Platform The Raman spectroscopy in-situ quantitative detection system (RiP system) was developed by the Institute of Oceanology, Chinese Academy of Sciences. Relying on the deep-sea ROV platform for near-seafloor in-situ detection, the system underwent lightweight modification and dual-control system upgrades after breakthroughs in key components such as laser Raman spectrometers and probes. The RiP system has successfully completed scientific expedition tasks during the program' s 2015 and 2016 cold seep-hydrothermal comprehensive cruises, conducting in-situ Raman spectroscopy detection in targeted areas including the Manus hydrothermal zone, Okinawa Trough hydrothermal zone, and northern South China Sea cold seep area, and carrying out a series of scientific application experiments.

For the first time in China, exposed natural gas hydrate was discovered on the seafloor. Surface natural gas hydrate was found beneath biological communities near cold seep vents, and the RiP system obtained in-situ Raman spectra of natural gas hydrate samples in the deep sea. The Raman spectral data indicated they were standard Type I hydrates.

To study the influence of the cold seep vent environment on natural gas hydrate formation and decomposition processes, the RiP system conducted in-situ Raman spectroscopy detection of the rapid hydrate formation process from venting gases near cold seep vents in the South China Sea ([Figure 6: see original paper]). For the first time, dissolved or suspended elemental sulfur (S) was discovered in the overlying water beneath cold seep biological communities, showing some correlation with sulfate (SO ^{2}) and CH concentration and depth. Through repeated experiments during two cruises in 2016, this correlation was verified, allowing the anaerobic oxidation of methane (AOM) process to be extended from the sediment layer to the overlying water beneath biological communities. This suggests a new oxidation reaction may exist with microorganisms participating in the further oxidation of hydrogen sulfide to elemental sulfur, representing a first internationally.

In-situ Raman spectroscopy detection was conducted on hydrothermal vent fluids at different temperatures and special systems near hydrothermal vents. During the 2015 cold seep-hydrothermal comprehensive cruise, the RiP system performed in-situ Raman spectroscopy detection on black and white smokers in the Manus hydrothermal zone, obtaining typical Raman spectra of chemical components in fluids near black smoker vents (280°C). During the 2016 cruise, the RiP system conducted in-situ Raman spectroscopy detection on liquid CO pools near hydrothermal vents in the Okinawa Trough.

Current research results provide new ideas and methods for marine chemical analysis in extreme regions such as deep-sea hydrothermal vents and cold seeps, offering strong data support for studying the formation mechanisms of cold seeps and hydrothermal vents and material-energy exchange processes.

2.3.2 Deep-water Visual Controllable Lightweight Sediment Coring System The deep-water visual controllable lightweight sediment coring system (coring system) was developed by the Institute of Oceanology, Chinese Academy of Sciences. While engineering the 3,500 m coring system, a 6,000 m coring system was also developed.

In March 2014, the 3,500 m coring system obtained approximately 12.5 m of sediment core samples during sea trials in cold seep and hydrothermal areas, with the longest sample reaching about 285 cm. During the 2015 program cruise, the improved 3,500 m coring system obtained about 52.5 m of sediment cores in the South China Sea cold seep and Manus hydrothermal work areas, with the longest sample reaching 10.9 m and a maximum recovery rate of 90.8%. The sediment samples were processed by extracting pore water at 10 cm intervals, yielding 510 layered pore water samples. For the first time in China, sediment core samples were obtained from the Manus hydrothermal area. The 3,500 m coring system sea trial and obtained samples are shown in [Figure 7: see original paper].

During the 2016 program cruise, the 6,000 m coring system was sea-trialed and applied to sampling and survey work, obtaining about 50 m of samples with a maximum length of approximately 6.4 m and a maximum recovery rate of 80%. On-site 10 cm interval pore water extraction from sediment samples yielded 300 layered pore water samples.

Using pore water research as an example: Cold seep fluids in the South China Sea are rich in CH . During upward migration along preferential channels driven by buoyancy, these fluids can effectively change the content of sulfate, calcium ions, and other components in pore water through the action of anaerobic methane-oxidizing bacteria and sulfate-reducing bacteria. If these methane-rich fluids originate from natural gas hydrate decomposition in cold seep areas, the large amount of water released would reduce the content of conservative ions such as chloride and sodium, and the ^{1} O value of water molecules would also show indications. Therefore, the content of characteristic ions in pore water is an important indicator for studying seafloor fluid activity.

Both the 3,500 m and 6,500 m coring systems have successfully completed sea trials and applications, obtaining large quantities of valuable samples that effectively support the program’ s research on sediment geochemical characteristics and sedimentary environment evolution in various study areas.

2.4 Summary

To meet the program’ s scientific requirements, the project’ s deep-sea marine detection equipment has achieved certain research results after development, testing, and application, providing advanced, practical, and reliable technical means for the program’ s scientific research. In 2017, the project will focus on scientific objectives to construct a heterogeneous marine detection equipment application system, comprehensively utilizing different types of equipment developed by the project to carry out multi-system collaborative three-dimensional observation and operations at different depths and scales, providing valuable multi-parameter collaborative observation data for scientific research.

3. Development Prospects

Human understanding of the ocean is a long and gradual process that requires marine technology equipment with longer working time, greater voyage range, deeper depth, stronger operational capabilities, and higher intelligence. Based on understanding the ocean, the ultimate goals are to utilize and develop marine resources. With technological innovation and progress, and the development of deep-sea technology equipment toward practicality, reliability, and intelligence, China’ s deep-sea technology and equipment will play important roles in marine scientific research and national economic services.

(1) **From Single Equipment to Diverse, Clustered Equipment:** Building upon single-unit technology, the project will expand group-style marine technology equipment to achieve autonomous collaborative detection and operation across global ocean areas, constructing a multi-marine detection equipment integration and demonstration system based on marine scientific research objectives. This will form comprehensive long-term, collaborative, multi-system, low-cost, full three-dimensional marine information detection and operation capabilities. Using the project' s sea-trialed technology equipment and combining it with scientific objectives, the project will conduct multi-type, multi-unit, multi-purpose marine equipment integration demonstrations and carry out exemplary applications. Utilizing various types of equipment for three-dimensional observations at different depths and scales will provide valuable multi-parameter collaborative observation data for scientific research, laying a solid technical foundation for organic integration with national special programs.

(2) **Transformation of Human Marine Activity Types:** Strengthening research and development of deep-sea equipment with operational capabilities will enable the transformation of human marine activities from information-gathering to operational types. This involves enriching and improving marine equipment' s detection and operational capabilities to achieve the ultimate goal of autonomous operation. The transformation from information to operation represents an important development trend for deep-sea technology equipment. Human understanding of the ocean is a long-term endeavor. Through continuous efforts to develop marine equipment with higher intelligence and stronger operational capabilities, the goals of utilizing and developing marine resources can be gradually realized, achieving the transition from observation to detection and ultimately to operation.

(3) **Further Enhancing Practicality, Reliability, and Intelligence:** Building upon program objectives, the project will expand new solutions for solving marine scientific problems and pioneer an unmanned era for marine detection and research. With the comprehensive entry of marine technology equipment into the unmanned era, intelligent marine robots with large-area detection and fine operation capabilities will lead the development of marine technology equipment, providing powerful technical means for studying marine scientific problems. Using unmanned research vessels as support platforms on the sea surface and unmanned research stations as support platforms underwater, the project will move land-based laboratories to the seafloor to study the ocean from both the sea surface downward and the seafloor upward. Relying on these two support platforms to provide energy replenishment and information interaction for unmanned systems in the ocean, the project will establish a long-term comprehensive three-dimensional unmanned detection and operation system based on marine robots. This will completely change the current human-centered research model and create a future research

model centered on groups of highly intelligent marine robots, providing high-value scientific data for marine science research and making greater contributions to humanity' s better development and utilization of the ocean.

4. Conclusion

The successful implementation of the CAS Marine Pilot Program has driven the development and progress of deep-sea marine technology. Aimed at the program's scientific objectives, the project has achieved a batch of original scientific and technological achievements, enhanced China' s scientific and technological innovation capabilities in the marine field, and made important contributions to the innovative and leapfrog development of China' s scientific and technological endeavors. The Marine Pilot Program, for the first time, treats the ocean as an integrated whole from a systematic perspective, with organic connections between various projects. Technology provides advanced detection means for science, and deep-sea technology equipment itself has gradually formed an organic whole, constructing a technical system oriented toward marine scientific research. Aimed at scientific questions, various types of marine equipment with different functions and depth ratings can conduct collaborative observations, obtaining large amounts of multi-parameter scientific data and providing a new technical solution and approach for humanity' s exploration and understanding of the ocean in the unmanned era.

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