Front. Eng. Manag. 2023, 10(3): 546–549
https://doi.org/10.1007/s42524-023-0260-6

SUPER ENGINEERING

Yuangui TANG, Shuo LI

Development and deep-sea exploration of the Haidou-1

© Higher Education Press 2023

Keywords hadal zone, autonomous and remotely-operated vehicle, integrated exploration operation, deep dive exceeding 10000 meters

Undertaking unit: Shenyang Institute of Automation, Chinese Academy of Sciences
Participating units: Institute of Deep-sea Science and Engineering, Chinese Academy of Sciences; Institute of Acoustics, Chinese Academy of Sciences; Harbin Engineering University; Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences; Tsinghua University; Institute of Mechanics, Chinese Academy of Sciences; Zhejiang University; Institute of Automation, Chinese Academy of Sciences; 21st Research Institute of China Electronics Technology Group Corporation

1 Introduction

The Haidou-1 Autonomous and Remotely-operated Vehicle (hereinafter referred to as Haidou-1) (Fig. 1) has been developed to address the significant demands for core key technologies and equipment in China's deep and distant seas. The vehicle is capable of covering all global ocean depths up to a maximum of 11000 meters. Full-ocean-depth underwater vehicles represent one of the highest technological and capability benchmarks in current international marine science research.

The hadal zone typically refers to oceanic regions with depths exceeding 6000 meters, representing the limit of human exploration in deep-sea research. In particular, abyssal depths exceeding 10000 meters, due to their unique environments and extreme technical challenges, remain largely unexplored and inaccessible to humans. Limited by deep-sea technology and equipment, our understanding of abyssal life, the environment, and geological processes remains scarce, and abyssal science is emerging as the latest frontier in international marine science research. Existing deep-sea technologies are insufficient to meet the demands of abyssal research, and there is an urgent need to develop full-ocean-depth underwater vehicles with abyssal detection and sampling capabilities.

The Haidou-1 project is centered around China's strategic development plan for deep and distant seas. It aims to address frontier scientific questions in abyssal life evolution and environmental and geological changes, break through core key technologies for abyssal submersibles, and develop a full-ocean-depth autonomous underwater remotely operated vehicle with independent intellectual property rights that is capable of extensive autonomous navigation, precise exploration, and sampling operations. This advanced marine equipment will provide support for detailed investigations, near-seabed detection, and full-ocean-depth sampling operations in abyssal scientific expeditions.

After five years of concerted efforts, the fully independent Haidou-1 full-ocean-depth underwater robot was successfully developed. In 2020, Haidou-1 completed a

Fig. 1 The Haidou-1 Autonomous and Remotely-operated Vehicle.

Received April 21, 2023

Yuangui TANG, Shuo LI (✉)
State Key Laboratory of Robotics, Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang 110016, China; Institute for Robotics and Intelligent Manufacturing, Chinese Academy of Sciences, Shenyang 110169, China; Key Laboratory of Marine Robotics, Liaoning Province, Shenyang 110169, China
E-mail: shuoli@sia.cn

successful dive exceeding 10000 meters in depth, achieving China's first sampling operation at this depth and marking a new era in the country's full-ocean-depth operations. In 2021, Haidou-1 successfully completed a scientific expedition exceeding 10000 meters, becoming the first international expedition to achieve a full-coverage survey and detection of the Challenger Deep's western depression. This accomplishment propelled China's marine scientific expeditions into a new stage of "deep-sea exploration". Haidou-1 has set multiple world records in aspects such as seafloor navigation time, distance, and detection coverage, filling the international application gap for full-ocean-depth underwater vehicles at depths exceeding 10000 meters.

2 Technological breakthroughs and innovations

Haidou-1 is China's first piece of major equipment capable of reaching depths exceeding 10000 meters, overcoming numerous international challenges and achieving a number of groundbreaking scientific and technological innovations, leading the development of China's deep-sea underwater robotics and equipment.

(1) Adaptive technology breakthroughs in underwater vehicles capable of handling extreme depths, solving safety challenges in complex abyssal environments

The high-pressure, low-temperature, and dark abyssal environment poses severe challenges to the safety and survival of underwater vehicles. Extreme depths, immense hydrostatic pressure, and large gradient pressure variations render traditional pressure-bearing and sealing methods for underwater vehicles inadequate for long-term and reliable applications at these depths. Achieving pressure adaptability at extreme depths has become a critical factor in the success of full-ocean-depth underwater vehicles. Drawing upon the research team's technical expertise in the field of deep-sea underwater robotics, this project has developed compensatory pressure-bearing sealing technology and a novel process for encapsulating pressure-bearing components. This innovation achieves pressure balance between the interior and exterior of the electronic component hull while isolating it from the surrounding seawater. Consequently, the project has resolved the technical challenges of pressure-bearing and sealing at depths exceeding 10000 meters, enabling underwater vehicles to adapt to extreme pressure. By inventing a series of technologies for encapsulating and isolating electrical components and control units suitable for high-pressure oil-filled environments, the project has overcome the difficulties of pressure-bearing and power isolation and distribution in oil-immersed electrical control systems, which has established the continuous and stable operation capabilities of the Haidou-1 key electrical control components in high-pressure oil-immersed environments, ensuring the reliability, stability, and safety of the underwater vehicles operating at the bottom of the 10000-meter abyss. Owing to the breakthrough of this pivotal technology, the Haidou series of full-ocean-depth underwater vehicles have achieved a significant milestone in China's underwater robotics, enabling them to dive to depths exceeding 10000 meters. These vehicles have successfully carried out multiple deep dives and scientific expeditions, propelling China's deep-sea scientific research into the era of depths exceeding 10000 meters.

(2) Advancements in autonomous and remotely-operated hybrid control technologies for underwater robotics, developing a new control paradigm for extreme deep-sea environments

The deep hadal zone that exceeds 10000 meters represents a highly challenging and complex unstructured environment for underwater vehicles, demanding exceptional emergency response, decision-making, and management capabilities. Given the current limitations of underwater vehicles in autonomous sensing, recognition, and positioning capabilities at such depths, this project has proposed an autonomous and remotely-operated multi-mode control strategy for extreme marine environments. According to scientific research needs and without changing the basic configuration of the robot, it can flexibly switch among autonomous, remotely-operated, and hybrid control modes to efficiently execute research tasks. For wide-range cruising and detection, the Haidou-1 can operate in a tetherless autonomous mode, employing autonomous underwater vehicle (AUV) control methods for diving and autonomously completing extensive near-seabed cruising and exploration. When dealing with localized or fixed-point tasks at the seafloor, Haidou-1 can use a tethered remotely-operated control mode, similar to a remote operated vehicle (ROV), to conduct precise operations at fixed locations. For missions requiring search and location within a certain range, as well as target identification tasks, Haidou-1 adopts a hybrid autonomous and remotely-operated control mode, combining autonomous searching with manual location and identification before switching to remote control operations to complete both detection and operation tasks. Through sea trial verification, the project team has developed a multi-mode control technology system based on human–machine collaboration and integration concepts. This system fully exploits the control modes that combine wide-range autonomous cruising and detection with fixed-point remote control precision operations, enabling real-time dynamic switching of control modes oriented towards scientific research goals, forming online adjustment and flexible adaptation capability for the complex and diverse mission tasks in the abyssal depths. This advancement propels China's underwater robotics into a new phase of deep-sea scientific research exceeding 10000 meters.

(3) Breakthroughs in long-distance deep-sea soft optical fiber micro-cable modeling and application, realizing real-time transmission of video images for deep hadal zone

Optical fiber micro-cables are effective media for enabling real-time communication, video transmission, remote control operations, and other human–machine interactions in full-ocean-depth underwater vehicles. However, optical fiber micro-cables are inherently fragile and prone to breakage when bent, potentially leading to unexpected communication disruptions. From the turbulent sea surface to the deep-water zones with undercurrents and to the complex seabed in the 10000-meter abyss, optical fiber micro-cables must overcome numerous challenges, such as breakage, tension rupture, or signal attenuation. Considering the safety concerns of using optical fiber micro-cables, and the hydrodynamic properties of optical fiber micro-cables in deep-sea environments, this project constructs a physical property model of soft optical fiber micro-cables. Based on the model's analysis, comprehensive management solution and device for adaptive optical fiber micro-cable were invented. This system compensates for disturbances in the marine environment through automatic release, overcoming the hydrodynamic effects of complex ocean waters and seabed environments on fine optical fibers, thereby ensuring the stability and reliability of full-ocean-depth optical fiber communication links. Owing to this technological breakthrough, Haidou-1 has successfully achieved real-time transmission of high-definition video images from the hadal zone exceeding 10000 meters. Scientists can now observe seafloor topography, benthic organisms, and geological structures in real-time. Additionally, leveraging real-time optical fiber communication, operators can remotely control the Haidou-1 robotic arm, enabling China's first-ever mechanical arm sampling operation at the deep-sea floor exceeding 10000 meters, thus China's first batch of deep-sea abyss samples were obtained, which help scientists better understand the deepest regions of the hadal zone (depths exceeding 10000 meters).

(4) Breakthroughs in integrated and optimized design technology for detection and operation, forming efficient full-ocean-depth precise detection and dexterous operation capabilities

Detection and operation are two typical marine scientific research application modes for underwater vehicles. Traditional underwater vehicles usually focus on one of these tasks, resulting in limited overall efficiency. The full-ocean-depth exceeding 10000 meters represents a typical unstructured and complex environment. Full-ocean-depth underwater vehicles take several hours to reach this depth, where they must address both extensive detection requirements and localized operation tasks, which necessitates efficient performance. Closely aligned with scientific research and application needs, this project proposes a highly integrated optimization design method for full-ocean-depth underwater vehicles that combines detection and operation. It rationally incorporates multiple acoustic detection devices, high-definition cameras, depth detection equipment, temperature detection devices, and auxiliary lighting systems, providing foundational conditions for comprehensive abyssal exploration. Meanwhile, Haidou-1 is equipped with a seven-function electric manipulator, sediment samplers, and water sampling bottles, enabling efficient sampling operations at depths exceeding 10000 meters (Figs. 2 and 3). In 2020, Haidou-1 successfully achieved China's first 10000-meter deep-sea detection and operation. In 2021, Haidou-1 focused on scientific research objectives and efficiently executed detection and operation tasks. Globally for the first time it accomplished wide-ranging, full-coverage cruising and detection of the western depression area of the Challenger Deep and precise full-ocean-depth electric manipulator sampling operations at depths exceeding 10000 meters. These achievements have made significant contributions to international abyssal technology advancements and global marine geophysics research.

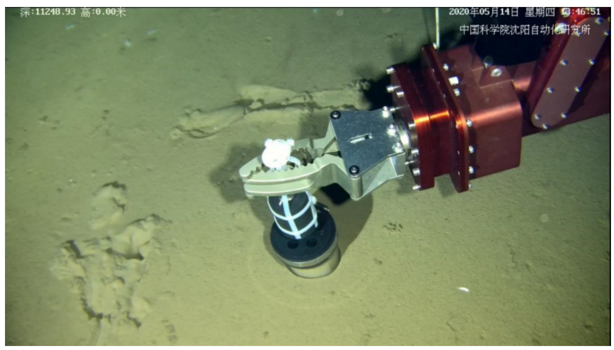

Fig. 2 Underwater sediment sampling of Haidou-1 at depths exceeding 10000 meters.

Fig. 3 Underwater manipulator grabbing of Haidou-1 at depths exceeding 10000 meters.

3 Conclusions

From July 2016 to October 2021, after more than five years of research, development, and sea trials, Haidou-1 accomplished China's full-ocean-depth underwater robotic mission tasks for deep dives exceeding 10000 meters and related scientific research and applications, achieving inspiring and significant technological innovations that propelled China's full-ocean-depth underwater vehicles into a new stage of scientific research and applications at depths exceeding 10000 meters. Looking toward the future, the journey of exploration and research in the deep hadal zone exceeding 10000 meters is long and arduous, and deep-sea technology breakthroughs and research efforts will never cease.