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# Development of Autonomous Underwater Vehicles Technology

**Wu Yousheng [1], Zhao Yiyu [2], Lang Shuyan [2], Wang Chuanrong [2]**

1. China Ship Scientific Research Center, Wuxi 214082, Jiangsu, China
2. Shipbuilding Information Center of China, Beijing 100101, China

**Abstract:** Unmanned submersibles are important for deep-sea exploration, and have become a key development direction for marine equipment worldwide. This study proposes a technical system layout for autonomous underwater vehicle (AUV) development in China by 2035. To this end, we first systematically summarized the current progress made worldwide regarding AUVs in terms of development plans, research, and application, and analyzed the technical trends and prospects of AUVs by 2035. Subsequently, we introduced the development status of AUVs in China and explored its challenges in top-level planning, equipment development, and industrialization. In conclusion, China should identify materials and reliability as its basic research directions for AUVs and focus its efforts on breakthroughs in key technologies, including perception, communication/navigation, energy, autonomous navigation, and cooperative operation. Furthermore, we propose a preliminary plan for major scientific and technological projects that aim to promote the pedigree and localization of AUVs in China and offer some policy suggestions for the high-quality development of the industry in China from the perspectives of top-level planning, industry coordination, policy guidance, and personnel training.
**Keywords:** deep-sea exploration; autonomous underwater vehicles; development trend; key technologies; fundamental research

## 1 Introduction

With the increasing scarcity of land and offshore resources, mankind has begun exploring the deep sea. Owing to harsh underwater environments and limited diving depths, unmanned underwater vehicles have become important tools for deep-sea exploration and development. Driven by artificial intelligence, detection and identification, intelligent control, system integration, and other technologies, autonomous underwater vehicles (AUVs) can efficiently complete various underwater tasks based on their own decision-making and control capabilities, which have become important equipment developed by the world's maritime powers [1]. In the future, AUVs will play more important roles in marine safety maintenance, marine resource development, and marine scientific research.

At present, some researchers have completed a summary of research on AUV technologies [2–6], focusing on their status and judging their trends. However, there has been a lack of research on the development strategy of AUV technologies in the medium and long terms, particularly the future layout of AUV technology in China. Taking the development of AUV technology by 2035 as the research breakthrough, this paper mainly studies the advanced level and frontier issues, development trends, key tasks, preliminary plans of major scientific and technological projects, and policy suggestions at the international level to provide a reference for the development of China's AUV industry and technology.

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**Corresponding author:** Wang Chuanrong, researcher of Shipbuilding Information Center of China. Major research field is marine equipment technology. E-mail: wcrerc@163.com

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# 2 Summary of advanced level and frontier issues of AUVs internationally

## 2.1 Global policy and action plan

To promote the development of AUVs, major maritime countries have formulated relevant research and development plans. In September 2011, the United States released the *Key Infrastructure for Marine Research and Social Needs in 2030* report, which put forward suggestions for the planning and construction of various marine research infrastructures such as observation platforms, including autonomous underwater gliders (AUGs) and underwater robots) in 2030 [7]. In 2016, the United States released the *2025 Autonomous Submarine Demand* report, proposing improvements to the independence of AUVs and ensuring that they can run for days or weeks with minimal human intervention [8]. In 2018, the United States released the *National Marine Science and Technology Development in the United States: Vision for the Next Ten Years* report, proposing the development of ships, submersibles, and other equipment [9]. In recent years, the Advanced Research Projects Agency (DARPA) of the U.S. Department of Defense has focused on unmanned underwater systems, underwater situational awareness, and underwater and cross-domain communications, and is developing new long-haul, long-distance unmanned underwater vehicles, as well as advanced autonomous underwater vehicle systems.

In 2015, Japan deployed AUVs for resource exploration, high-efficiency offshore operation systems for remote operated vehicles (ROVs), and the development of cooperative multi-AUV operations in the key science and technology projects applying next-generation robots [10]. In the same year, Lloyd’s Register of Shipping and others launched the *Global Ocean Technology Trends 2030* report, proposing that a series of autonomous underwater, surface, and air equipment will complete joint autonomous actions and tasks in the future, which can provide a new approach to exploration, monitoring, and interaction with marine space [11].

## 2.2 Global R&D and application status

2.2.1 AUVs have been widely used in deep-sea exploration and operation

Many maritime countries have developed multi-type AUVs (Table 1). The United States, Japan, and France are in leading positions in the AUV technology field and have formed new industries and mature markets. To improve the ability of marine surveys and the level of underwater vehicle technology, the Woods Hole Oceanographic Institution developed a 6500-m Sentry AUV, which was tested at sea and applied in 2008. Japan’s Mitsui Shipbuilding Co., Ltd. and the University of Tokyo jointly developed an r2D4 AUV with a depth of 4000 m, which was used to investigate submarine hydrothermal activity in the mid-ocean ridge. The 1000–4500-m AUVs developed by Kansberg of Norway are being used for high-quality marine surveying and mapping, channel survey, and rapid environmental assessments, among other uses. The National Oceanographic Research Institute in Southampton, UK is developing a next-generation 2000-m AUV, which can create detailed maps and determine the habitat characteristics of the seabed in polar regions covered with ice and snow [12,13]. In general, the degree of intelligence in AUVs is still at the primary stage, and has the basic characteristics of pre-programming, emergency obstacle avoidance, data acquisition, and single station detection.

**Table 1.** Typical foreign AUVs.

| Country | Name | Operating depth (m) | Mass (kg) | Endurance (h) |
|---|---|---|---|---|
| USA | Bluefin9 | 200 | 60.5 | 12 |
| | Bluefin21 | 4500 | 750 | 25 |
| | Sentry | 6000 | 1250 | 20 |
| Norway | REMUS 6000 | 6000 | 884 | 22 |
| | HUGIN 4500 | 4500 | 1900 | 60 |
| UK | Autosub 6000 | 6000 | 1800 | 30 |
| Japan | r2D4 | 4000 | 1630 | 12 |
| France | Alister-9 | 100, 200 | 50–90 | 24 |

2.2.2 Development of new AUV types

An AUG is a new type of AUV that was developed in the 1990s. Single glider technology in the United States is extremely mature, and there are many glider products (Table 2) that are highly reliable, practical, and widely utilized. In 2009, France successfully developed SeaExplorer, which has been put into practical use and commercialized. In addition, Japan, Canada, South Korea, New Zealand, and other countries have also carried out research and

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development of AUGs. To date, various types of AUGs, such as multi-mode hybrid propulsion gliders, flying wing gliders, temperature difference energy gliders, and wave gliders, have been developed, and their performances such as maneuverability, reliability, and stealth have been continuously improved. In addition, the United States, Sweden, and South Korea are developing autonomous/remote-operated composite underwater vehicles (ARVs). Popular ARVs include Poseidon and N11k, which can not only sail and operate autonomously, but also complete tasks through remote control [14–16].

**Table 2.** Typical AUGs of USA.

| Name | Mass (kg) | Load capacity (kg) | Operating depth (m) | Gliding speed (kn) | Duration or working hours (days) |
|---|---|---|---|---|---|
| Spray | 51 | 3.5 | 1500 | 0.5 | 33 (duration hours) |
| Slocum | 52 | 5 | 200, 1000 | 0.7 | 20 (duration hours) |
| Seaglider | 52 | 4 | 1000 | 0.5 | 200 (duration hours) |
| Ant littoral | 110 | 5 | 200 | 2 | 30 (working hours) |
| Tethys | 120 | – | – | 1–2 | 31 (working hours) |

*Note*: 1 kn = 1.852 km/h.

2.2.3 The ultra-large AUV has become a hot spot

The United States and Russia are developing ultra-large AUVs weighing tens of tons including Echo Voyager, Manta, and Poseidon [5]. The related testing of Echo Voyager is progressing smoothly. Echo Voyager is approximately 15 m long, weighs 50 tons, and has a maximum operating depth of 3353 m. It uses oil and electricity as a hybrid power source, with a maximum underwater speed of approximately 14.5 km per hour and a total journey of approximately $1.2 \times 10^4$ km. It also has its own sonar-obstacle avoidance and inertial navigation systems. Based on the design of Echo Voyager, Boeing is developing Orca ultra-large AUV, which can be quickly configured to carry different types of loads according to the mission requirements.

### 2.3 Development status of AUVs in China

2.3.1 Development status

Research on AUVs in China started late but has developed rapidly [6]. In recent years, the national key research and development plan of China has also supported research on unmanned full ocean depth underwater vehicles, autonomous obstacle avoidance, and planning control of underwater vehicles, which has continuously improved the operational capability and intelligence level of such vehicles. The CR-01 and CR-02 AUVs developed in China can detect seabed topography and shallow stratum profiles up to 6000 m deep. The performance indicators of serialized AUVs have been continuously improved to meet the needs of ocean mineral resource exploration and ocean scientific investigation (Table 3). In addition, Haiyan series AUGs with completely independent intellectual property rights have a maximum working depth of 10 619 m. Haidou autonomous/remote-operated composite underwater vehicles with a maximum depth of 10 767 m, have also made China the third country with the ability to develop 10,000-m unmanned underwater vehicles after Japan and the United States. Moreover, Tansuo 1000 was used for the first time in the 35th Antarctic expedition of China, allowing China's AUV technology to officially enter the stage of polar ocean observation.

**Table 3.** Typical AUVs and AUGs of China.

| Name | Operating depth (m) | Speed (kn) | Endurance | Mass (kg) |
|---|---|---|---|---|
| CR-02 | 6000 | 2.3 | 25 h | 1500 |
| Qianlong I | 6000 | 2 | 30 h | 1500 |
| Qianlong II | 4500 | 2 | 30 h | 15 000 |
| Qianlong III | 4500 | 2 | 40 h | 15 000 |
| Tansuo 4500 | 4500 | 2 | 20 h | 15 000 |
| Tansuo 1000 | 800 | 2–5 | 300 km, 30 d | 1200 |
| Haiyan (AUG) | 1500 | 1.3 | 1000 km, 30 d | 70 |
| Haiyi series (AUG) | 300–7000 | 0.5–1 | >1000 km | 60–70 |

2.3.2 Existing problems

There has been a lack of studies on systematic planning and development. At present, research on AUVs is mainly based on the analysis of current industry demand and the understanding of foreign-related technology development.

However, systematic research on the equipment and technology development planning of AUVs has yet to be conducted.

The development of key support equipment has also lagged. There has been a lack of specialized research on core devices such as sensing devices and active control devices necessary for AUVs in China, resulting in the development of special equipment lagging far behind that of the overall integration technology. The related supporting market has become monopolized by foreign products.

The industrialization process is slow, and although China has made a breakthrough in its types and localization of AUVs, the process of equipment commercialization and industrialization has been slow. The equipment used for engineering applications is mainly purchased or leased from abroad.

## 3 Development trend of AUVs

### 3.1 Technology trend

*Farther sailing*. At present, the fuel cells and small nuclear energy being studied worldwide have the characteristics of a small size and high energy density, which can greatly improve the endurance of the AUVs. In addition, non-traditional navigation methods suitable for underwater applications are being developed continuously, which can guarantee high-efficiency and high-precision underwater navigation and support AUVs to sail further.

*Deeper diving*. With the continuous development of material and sealing technologies, it has become the goal of many countries to develop and optimize intelligent AUV technologies for use at a 6000 m water depth or even the whole sea depth.

*High intelligence*. In the future, AUVs will continuously enhance their ability to perceive the environment and identify targets by jointly applying various detection and identification technologies, and their autonomous systems will also have a higher learning ability. At the same time, in terms of motion control and decision-making planning, AUVs will adopt more intelligent information processing methods [19].

*Cooperative operation*. With the increasing application of AUVs, in addition to single equipment used to conduct certain tasks, multiple autonomous and remote-operated underwater vehicles will be required to cooperate and complete more complex tasks. Through large-scale and multi-platform networking operations, marine detection and operation capabilities will be enhanced.

### 3.2 Development scenario forecast in 2035

In 2035, the ability of deep-sea exploration and operation will be significantly improved. Series of AUVs with different depths, different functions, different sizes, and high intelligence will have achieved modular development. They will have the basic characteristics of autonomous environment perception, autonomous navigation planning, autonomous operation, group cooperation, precise positioning and navigation, and long-term underwater operations. They will be used in deep seas (including abysses), polar underwater reconnaissance, scientific investigation, resource exploration, and development operations, and become the main force of deep-sea operations. At the same time, ultra-large manned equipment and cutting-edge intelligent unmanned technology will be organically integrated. All types of deep-sea equipment will realize efficient cooperative operation between manned and unmanned, small and large, local, or overall applications.

## 4 Key tasks for development of AUVs

### 4.1 Key technologies to be developed

4.1.1 Technology of autonomous perception analysis in deep-sea complex environment

Because of the complex and changeable deep-sea environment, the interference of marine life and water flow increases the difficulty of ocean detection perception and analysis. It is necessary to develop new technologies for deep-sea detection. Related technologies will be developed to improve the efficiency, reliability, and autonomy, and to solve the problems of storage, processing, and identification of large-capacity and various underwater data. Core technologies include sensors and system configuration technology for intelligent detection of deep-sea complex environments, environmental sensing/cognition and reasoning analysis technology, and multi-target autonomous tracking and identification technology.

4.1.2 Technologies for new communication and positioning navigation in deep seas

Deep-sea positioning and navigation are faced with a complex environment and lack of information sources,

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which makes the current deep-sea underwater acoustic communication non-ideal in terms of communication quality and stability. Developing new deep-sea communication, positioning, and navigation technologies with high precision, high efficiency, and high reliability has become a key aspect of future deep-sea exploration. Core technologies include optical communication technology in deep-sea environments, static and dynamic combined communication and positioning navigation, submarine high-precision positioning system, long-distance underwater high-speed communication and information exchange, extremely low-frequency electromagnetic wave application, submarine terrain matching positioning and navigation, and gravity field and geomagnetic field positioning and navigation technologies.

4.1.3 Technologies of efficient and safe energy supply for intelligent deep-sea unmanned equipment

To meet the increasing mission requirements, the endurance of intelligent deep-sea unmanned equipment is increasing. The battery affects the system performance in terms of both size and weight. The complexity of the power and energy supply technologies of intelligent deep-sea unmanned equipment is far beyond that of surface ships, and the volume and weight density of energy storage are the key factors for such application. Therefore, high-density and high-safety energy supply and storage technologies have become one of the main directions. Core technologies include high-pressure and corrosion-resistant high-density energy, underwater small-volume nuclear power, and deep-sea energy supply technologies.

4.1.4 Technologies of autonomous navigation and operation control of unmanned underwater equipment

In the absence of manual real-time control, unmanned underwater equipment can make timely and independent decisions according to its own state and external environment changes during navigation and operation, which is an important development direction for unmanned underwater equipment technologies. Core technologies include autonomous route planning technologies under complex underwater environments, intelligent navigation control technologies, information fusion and real-time transmission technologies, autonomous docking and recovery technologies, and autonomous attitude control technologies.

4.1.5 Technologies of intelligent collaboration of manned/unmanned underwater equipment cluster

The efficiency of a single underwater equipment is limited, as are the operational capabilities of different types of equipment. Cooperative operations of various underwater equipment will become an effective way to complete underwater complex tasks, which is the development direction of the new generation of deep-sea exploration and operation technologies. Core technologies include cluster equipment with multi-unit space and environment information perception/real-time fusion technologies; intelligent auxiliary control technologies such as a master–slave unit state judgment/anti-interference/space-time coordination/precise cooperation/fault diagnosis and automatic elimination; equipment docking and access technologies under an ultra-high pressure environment; and cluster cooperative operation management technologies.

### 4.2 Basic research direction of priority layout

4.2.1 Research on design, preparation, and application of advanced materials for deep-sea unmanned equipment

With the increasing depth of ocean development, deep-sea materials should have super-strength, intelligence, and self-repairing capabilities. Deep-sea materials mainly include metals, ceramics, polymers, and composite materials. Improving the strength, toughness, durability, and other usability functions through nanoscale design and applying these properties on large deep-sea structures is a basic problem to be solved in the future. It is necessary to conduct research on the composition design and performance of advanced materials, microstructure control and preparation methods of advanced materials, mechanical properties of advanced materials under deep-sea complex environments, environmental safety, and life cycle assessments of advanced materials.

4.2.2 Research on reliability of unmanned equipment in extreme deep-sea environments

Unmanned underwater equipment faces complex and extreme environmental factors while exploring and operating in the deep sea. Extreme deep-sea environments will induce unmanned underwater equipment failures, and thus reliability is a problem that must be solved. Research on safety design/intelligent monitoring and control technologies, fault analysis/hazard assessment and disposal technologies, simulation and verification technologies of deep-sea environmental conditions, and extreme environmental factors should be carried out.

## 5 Preliminary plan for major scientific and technological projects

### 5.1 Necessity

The autonomous ability of the developed AUVs is still not high, with a weak level of intelligence. The new generation of artificial intelligence technologies will greatly improve the intelligence level of underwater vehicles. The new communication, positioning, navigation technologies, and new energy technologies will also promote the reliability, efficiency, endurance, and cluster operation capabilities of AUVs.

China’s demand for deep-sea exploration and operation is gradually moving toward the entire sea depth. AUVs with different depths and capabilities should be applied according to different needs to improve the efficiency and reduce costs. At present, the localization level of core equipment of AUVs in China is low, and research and development progress is subject to foreign countries. In addition, there is no system for deep-sea intelligent exploration. Further breakthroughs need to be made in many fields, such as intelligent sensing, underwater positioning and coordination, control and navigation, and system safety and reliability.

### 5.2 Engineering tasks

Research and development of AUVs that adapt to different application environments and application loads and form genealogical AUVs that dive from shallow sea to a 10 000 m abyss covered detection and operation. Key breakthrough technologies such as independent detection and perception, deep-sea communication and positioning navigation, a highly efficient safe energy supply, autonomous navigation control, and collaborative operation, are needed to realize the transformation from scripted intelligence to adaptive intelligence. A localization of sensors and core components of AUVs should be developed, and the research and development capability of the entire industrial chain of AUVs with independent intellectual property rights should be formed.

### 5.3 Objectives and effects

Before 2025, the missing links of China’s AUV technology and industrial chains should be established, and the localization rate of key components of autonomous underwater vehicles should be improved. Autonomous collaborative detection and operation with various unmanned equipment should be realized.

Before 2035, the technical level of core equipment should be world-leading, with the capability of R&D, design, manufacturing, testing, support, and operation and maintenance of pedigree AUVs with independent intellectual property rights. The deep-sea intelligent unmanned cluster detection operation equipment and supporting industrial chain should develop maturely, which has led to the upgrading and development of industries such as advanced materials, new power sources, advanced manufacturing, and supporting equipment.

## 6 Countermeasures and suggestions

### 6.1 Make overall planning and ensure capital investment

The top-level design work and overall planning should be strengthened. Detailed research and development goals for AUVs should be formulated in stages and promoted in a gradual manner. Full play should be given to the overall strength of the country and industry, and guide relevant enterprises to unify the focus of technology research and development toward the determined key directions. Diversified investments in scientific research should be constantly increased to overcome important key technologies.

### 6.2 Increase industry coordination and deepen industry–university–research cooperation

Cross-disciplinary and cross-industry cooperation with advanced enterprises in data and information processing technology, communication technology, computer technology, and other related fields should be increased. A strategic alliance for technological innovation in the AUV industry should be built, cooperation of industry-university-research in this field should be deepened, and the transformation of technological achievements and industrialization of AUVs should be promoted.

### 6.3 Strengthen industrial management and promote policy guidance

The lack of management of AUV industrialization should be complemented by the relevant competent departments, and the overall management of funds, manpower, equipment, technology, and data resources should be

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strengthened. Industrial incentive policies should be implemented, such as "the first set of credit support and tax reduction and exemption" and "national allocation and national use" of a self-developed support equipment/system of AUVs.

### 6.4 Enhance personnel training with focus given to international cooperation

The training of leading and top young talent in the field of AUVs should be increased, high-level foreign talent should be attracted in various ways, and a reasonable and effective talent incentive and restraint system should be explored. Active participation should be made in the tasks of relevant international organizations, while vigorously carrying out international technology exchange activities, and actively participating in the formulation of international standards.

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