

Review

A Review of Subsea AUV Technology

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Abstract: The observation and detection of the subsea environment urgently require large-scale and long-term observation platforms. The design and development of subsea AUVs involve three key points: the subsea-adapted main body structure, agile motion performance that adapts to complex underwater environments, and underwater acoustic communication and positioning technology. This paper discusses the development and evolution of subsea AUVs before proposing solutions to underwater acoustic communication and positioning navigation schemes. It also studies key technologies for the agile motion of subsea AUVs and finally gives an example of a solution for implementing underwater AUVs, i.e., the disk-shaped autonomous underwater helicopter (AUH). This paper will provide guidance for the design of subsea AUVs and the development of corresponding observation and detection technologies.

Keywords: AUV; seabed; marine observation and detection; agile motion; underwater acoustic communication

1. Overview

The observation and detection of the subsea environment is an important way of exploring and studying the ocean, which is also crucial for building maritime power. The observation and detection of the subsea environment are also important for marine scientific research, resource detection, global climate change research, marine archaeology, and military target detection.

At present, the technical means for seabed observation and exploration are relatively limited and mainly include the deployment of submarine buoys, unmanned/manned underwater vehicles, and seabed observation networks. The submarine observation network utilizes cables (usually optoelectronic composite cables) to connect observation stations (i.e., Subsea Stations) on the seabed into a network, transmitting electricity as well as observation data. With the seabed observation network, we can conduct long-term, uninterrupted, and real-time multi-parameter monitoring of specific water bodies [1]. However, due to the fixed platforms of the seabed observation network and submarine buoys, the observation and detection range is rather limited, and as a result, underwater vehicles are still important platforms for the observation and detection of seabed movement.

However, the terrain and topography of the seabed are rugged and varied, with features such as seamounts, hills, ridges, and trenches. There exist significant practical limitations for traditional underwater vehicles when operating in complex terrains. The Deep Submergence Vehicle (DSV) can carry scientists to the seabed for direct observation, but its range of activity is extremely limited. The unmanned remotely operated vehicle (ROV) is connected to the deck control station through an umbilical cable, which restricts its mobility in limited space, thus the ROV cannot conduct large-scale observation and detection. The motion range of autonomous underwater vehicles (AUVs) or underwater



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gliders (AUGs) is not limited by umbilical cables, although transversal propellers are usually required to increase their maneuverability when operating near the seabed. Therefore, existing submersible platforms cannot provide sufficient support for subsea observation and exploration missions.

With the development of ocean technology, new forms of underwater vehicles gradually come into our vision, including underwater crawling machines that can directly move on the seabed and have been applied to long-term observation [2,3], deep-sea sampling [4], and other scenarios. Biomimetic submersibles have more flexible driving methods and stronger environmental adaptability by imitating the forms of marine organisms such as fish [5–7], manta rays [8–10], octopus [11,12], and crabs [13].

In recent years, with the expansion of the scope and period of underwater observation and exploration, the demand for submersible platforms has extended from fixed-point and short-term observations to large-scale and long-term three-dimensional collaborative observations. However, the existing traditional and fixed observation methods are limited by their respective technical characteristics and cannot collaborate efficiently, making it difficult to achieve effective observation and detection of the seabed environment. At present, there are a number of AUVs capable of performing multiple tasks in the seabed environment; nevertheless, benthic underwater vehicles are preferred to have long-term residential capability and high agility (Figure 1). Such unmanned autonomous mobile platforms are known as “subsea AUVs,” or subsea resident AUVs (RAUVs) [14] and subsea robots [15].

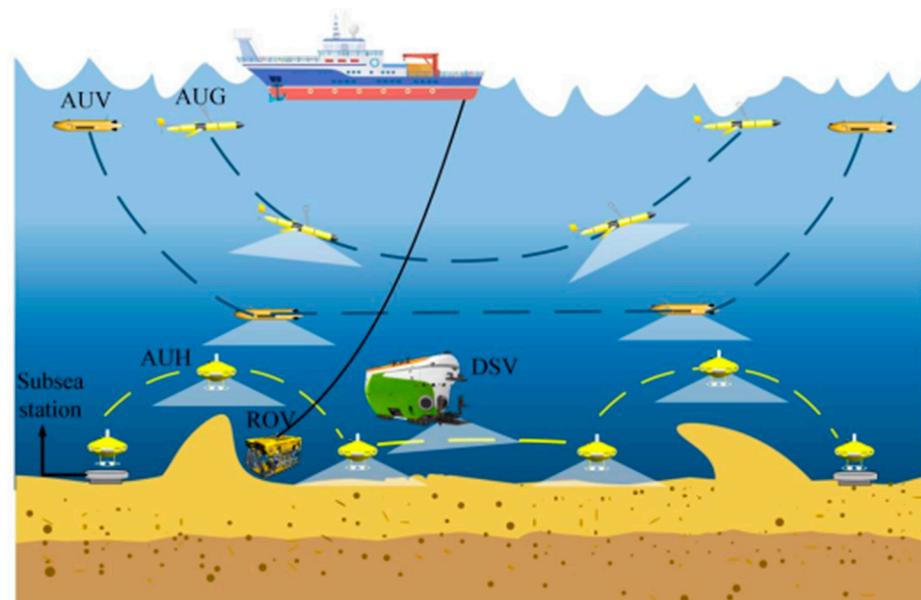


Figure 1. Operating range of various underwater robots in water bodies.

Since the world’s first AUV was developed by the University of Washington in the 1950s, the development of AUV has been ongoing for more than 60 years. With the development of computer technology and the increasing maturity of electronic technology, in the late 1990s, AUV entered a rapid development stage, and a number of influential AUVs were successfully developed and applied, including ABE in the United States, Autosub in the United Kingdom, and Theseus in Canada. AUV technology has come into a new development era since the beginning of the 21st century, with the emergence of an increasing number of commercialized AUVs such as Hydroid’s Bluefin series in the United States, Kongsberg’s REMUS and HUGIN series in Norway, and Teledyne’s Gavia series in the United States. AUV has entered the stage of practical application.

Traditional torpedo-shaped AUVs are mostly underactuated systems with strong nonlinearity and coupling in a control system. When AUV is applied to the seabed environ-

ment, considering the complexity of seabed fluid action and model parameter uncertainty, controlling the AUV is difficult. With the development of underwater technology and the expansion of application scenarios, AUV has emerged in various structural forms.

Saab Seaeye's Sabertooth AUV has a rectangular body structure (Figure 2a) and is neutrally buoyant, balancing endurance and maneuverability. Sabertooth AUV has a working depth of 2400 m and can switch between AUV and ROV operating modes. Flatfish AUV also has bottom-dwelling capabilities but has a different shape [16] (Figure 2b). Houston Mechatronics Inc.'s Aquanaut can deform to adapt to different operation scenarios. When sailing, it adopts a rectangular shape to effectively reduce motion resistance. When it reaches its destination, it can open its mechanical arm to perform operations (Figure 2c). Cellula Robotics Imotus is a low-speed, hoverable AUV used for small-scale continuous observation (Figure 2d). Eelume has a slender body structure that can be used for detection in narrow pipe spaces [17] (Figure 2e).

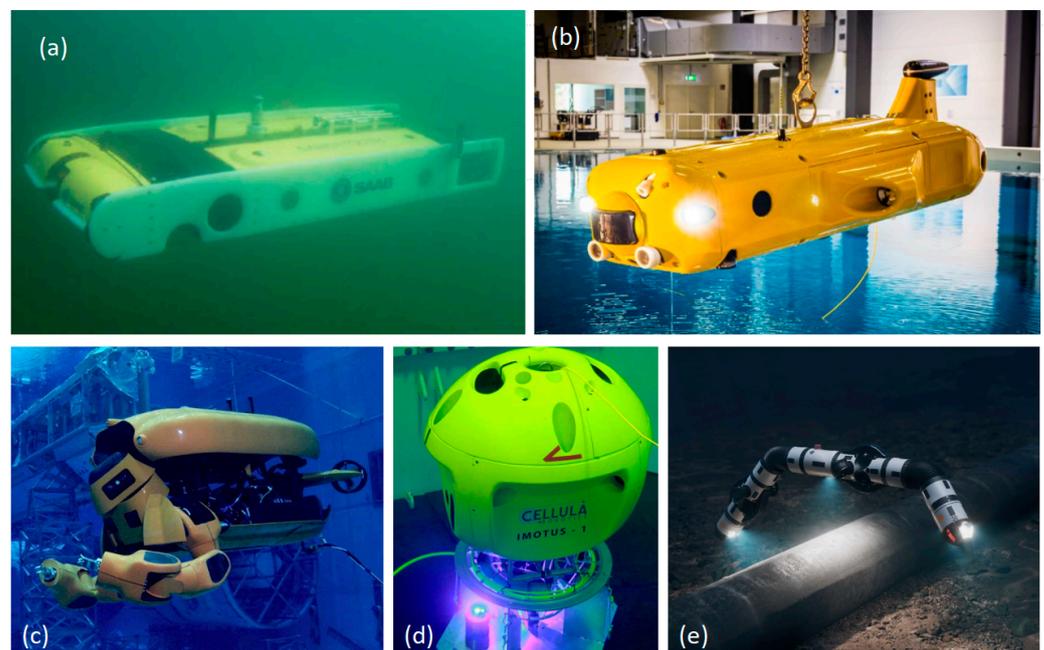


Figure 2. Various structural forms of AUVs [18–22]: (a) Saab Seaeye's Sabertooth AUV, (b) Flatfish AUV, (c) Houston Mechatronics Inc.'s Aquanaut, (d) Cellula Robotics Imotus, (e) Eelume.

Based on previous research, this paper intends to review and discuss the correlated technologies required more specifically for subsea AUVs, give one example of the subsea AUVs, and subsequently introduce the specific design considerations for the AUH.

2. The Mobility and Agility of Subsea AUV

Traditionally, the study of underwater vehicles mainly focuses on rapidity and endurance, especially when it comes to the maximum speed of AUV; however, there are few studies on its agility. Due to the complexity of the seabed environment, the maneuverability and agility of underwater vehicles are important indicators for the performance evaluation of subsea AUVs. Since there is no prior research on the agility of submersibles, we refer to the research on the maneuverability and agility of aerial vehicles [23,24] to explain the concept of agility of submersibles.

The agility of a submersible refers to its effectiveness and speed when it comes to changing its speed, direction, and location. The concept of agility also includes the concept of maneuverability, which refers to the ability to change speed, direction, and location while maintaining stability (Figure 3), as detailed below:

- (1) Speed mobility: On the one hand, this refers to faster and more stable seabed navigation capabilities, and on the other hand, it refers to the ability to work at extremely low speeds (including hovering, i.e., zero speed).
- (2) Direction mobility: This refers to the ability to turn and change pitch, yaw, and roll in three degrees of freedom, i.e., attitude control. Mobile submersibles need to have both instantaneous angular velocity and large-angle stability. Due to the need to quickly adapt to the complexity of seabed topography, direction mobility is particularly important for subsea AUVs.
- (3) Location mobility: This part is less considered during submersible design. It refers to the ability of the vehicle to move through different environments—air, land, water surface, water body, and seabed. For example, an amphibious aircraft needs to have the ability to fly in the air and dive underwater. For subsea AUVs, it is mainly about having stable operation capabilities, from landing on water bodies, diving to the seabed, and taking off from the seabed.

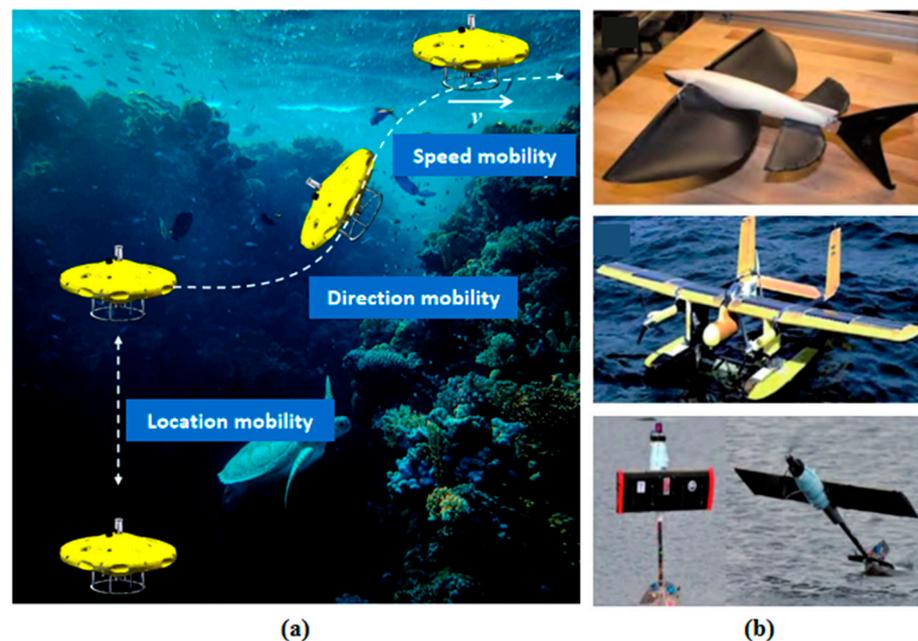


Figure 3. Mobility of the underwater vehicle: (a) illustration of speed, direction, and location mobility; (b) underwater vehicles with location mobility.

Agility refers to how quickly the vehicle changes its speed, direction, and location. Speed agility is the ability of the vehicle to accelerate or decelerate. Direction agility involves angular velocity and other quantities such as the turning radius of a submersible. Location agility refers to the time it takes for the vehicle to change locations. Agility provides necessary conditions for expanding the navigation performance and operational capabilities of submersibles and is a key focus of subsea AUV technology development.

In recent years, as the application scenarios have expanded, researchers have carried out preliminary work on the analysis and improvement of the agility of underwater vehicles. The design goal of traditional vehicles is to pursue increased mobility, that is, faster speed and higher propulsion efficiency, while there is less research on mobility in confined spaces and agility in complex seabed environments. In terms of directional agility, Kumar et al. [25] designed a split-shell submersible in which the agility of the vehicle is increased by optimizing the steering mode and lateral force and studied its impact on the control system of the vehicle. Gao et al. [26] designed a hybrid propulsion underwater vehicle with propellers and biomimetic fins. The hybrid drive mode makes the vehicle both fast and agile, making it more adaptable to complex marine environments. Inspired by amphibious/terrestrial animals, underwater vehicles with location agility have been

developed, including mechanical turtles [27] and four-finned biomimetic submersibles [28], all of which have the ability to change between land–water–seabed and other multi-sites.

To meet the demand for agile movement of subsea AUVs in complex seabed environments, it is necessary to first propose a body structure that adapts to complex seabed environments. Based on a certain body structure, we can carry out research on the influence of the bottom boundary of the seabed on the hydrodynamic performance of the subsea AUV and design a suitable propulsion mechanism to achieve agile movement of the subsea AUV, such as vector propulsion mechanism, based on hybrid propulsion (propeller propulsion and buoyancy adjustment) multi-dimensional attitude adjustment technology, as well as intelligent guidance methods adapted to complex seabed environments and other key technologies, to achieve the agility of subsea AUVs and meet the all-round observation and detection needs of the ocean seabed.

3. Evolution of the Subsea AUV Body Structure

The hydrodynamic performance of the AUV's body structure determines the stability of the vehicle as well as its speed and range under a limited energy load. Computational Fluid Dynamics (CFD) methods can be used for iterative optimization of AUV shape, without considering model scale effects, thus it is widely used in AUV hydrodynamic research [29,30]. Phillips et al. established a CFD algorithm to assist in the design of the AUV's hull line type and analyzed its motion stability and maneuverability [31]. Li et al. systematically studied the influence of Strouhal number and hull length-to-width ratio on the hydrodynamic performance of underwater gliders [32,33]. In terms of AUV shape hydrodynamic optimization research, Sun et al. were inspired by the shape of a sperm whale and designed a biological hydrodynamic shape for AUV based on an agent model optimization [34]. Honaryar and Ghiasi designed a shape similar to a catfish and thinned the edge of the hull to increase the turning speed of the AUV [35]. Alvarez et al. used a simulated annealing algorithm to optimize the shape of the AUV, sharpening the front and rear to improve its wave resistance near the free liquid surface [36]. Divsalar found that designing the front of the AUV as a bullet shape and designing the rear as a sharp shape can improve its hydrodynamic performance [37], all of which have improved the agility of the AUV. In terms of the hydrodynamic performance of submersibles at the sea bottom and sea surface, Du et al. analyzed the hydrodynamic characteristics of AUV cruising under sea bottom boundary influence and found that the drag coefficient increases as cruising height decreases [38]. Sakari and Rava analyzed the impact of sea surface waves on AUV using different turbulence models [39]. Wu et al. discussed the hydrodynamic performance of AUV docking with a conical seabed docking station during the docking process [40]. In terms of external structure, Wang et al. proposed to optimize the shape of the AUV bow to improve water entry stability [41], and Silva Costa et al. studied how to optimize the AUV tail structure to improve operation stability and maneuverability [42]. Research shows that the hydrodynamic structure of AUV has an extremely important impact on its maneuverability and flow-resistance ability, and its stability can be enhanced by optimizing its shape.

To determine the structure of AUVs that are suitable for the seabed environment, the stability of the complex seabed environment must be considered first. Generally, seabed AUVs include several structural forms (Figure 4): (1) Multi-body form, such as ABE AUV of Woods Hole Oceanographic Institution (WHOI), with a maximum depth of 6 km, an inspection distance of more than 30 km, and an inspection time of more than 50 h can perform seabed scientific investigations for a long time without the support of a mother ship. (2) Flat forms, such as WHOI's Sentry AUV and the 10,000-m "Sea Fighter" AUV of the Shenyang Institute of Automation of the Chinese Academy of Sciences; (3) Bionic type, such as Northwestern Polytechnical University's bionic ray AUV, and (4) Disc-shaped, such as Zhejiang University's underwater helicopter. Comparatively speaking, disc-shaped AUVs have greater advantages in terms of stability and agility.

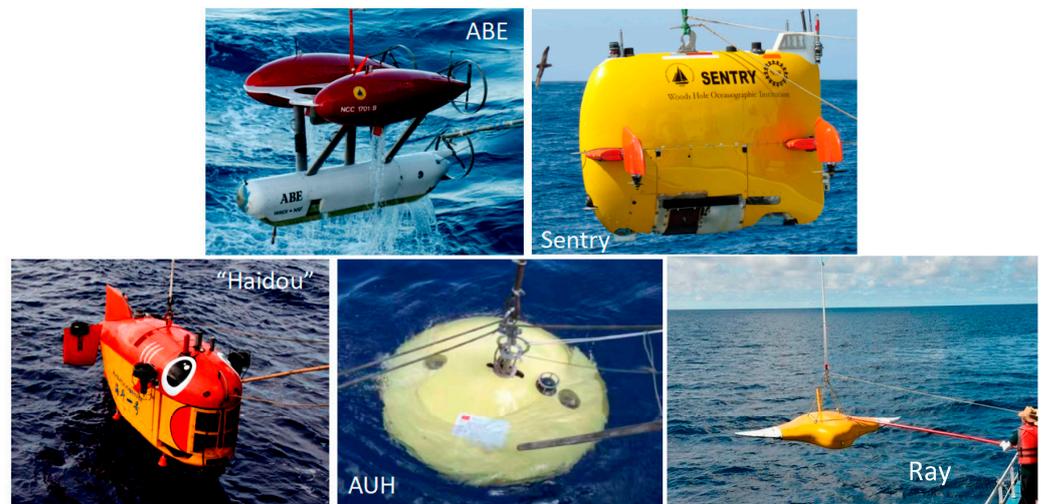


Figure 4. The body structure of the seabed AUV [43–47].

With the demand for seabed observation, new-concept subsea AUV technologies have developed rapidly in recent years. Northwestern Polytechnical University’s bionic electric ray AUV is a submersible that can be used for seabed cruising. Its body has a bionic structure, which can adapt well to the seabed working environment [47]. Zhejiang University’s Autonomous Underwater Helicopter (AUH) fully considers the seabed environment and has a disc-shaped body structure. Since it is significantly different from the traditional torpedo-shaped submersible in terms of shape, propulsion layout, and maneuvering characteristics, the hydrodynamic analysis theory for traditional AUVs cannot be fully applied to subsea AUVs such as AUH. At present, there has been some progress in the analysis and optimization of the hydrodynamic performance of such disc-shaped submersibles. For example, preliminary studies have been carried out on the drag reduction and route motion stability of disc-shaped submersibles [48] and hydrodynamic optimization based on disc-shaped structures has also been carried out [49,50]. As for the hydrodynamic problems of AUH near the seabed and sea surface boundaries, Chen et al. studied its hydrodynamic problems when approaching surface ships and considering wave effects [46] and the force situation during water entry [48]. Guo et al. conducted a preliminary study on the fluid resistance and the fluctuation phenomenon of AUH under the influence of seabed boundary effects [51].

It is undeniable that the utilization of body structures suitable for the seabed, compared with commonly used torpedo-shaped structures, will have a great impact on the hydrodynamic performance of subsea AUVs, which directly leads to a decrease in speed and endurance mileage. Therefore, seabed AUVs are suitable for seabed operations, but not for fast sailing and long-distance cruising. Although hydrodynamic optimization can improve speed and endurance mileage within a certain range for subsea AUVs, it is more important to highlight their stability in the seabed environment and their agility in adapting to this environment.

4. Seabed Acoustic Communication and Positioning Navigation Technology

The communication, positioning, and navigation system is one of the core systems of AUVs, which not only guarantees the reliable and safe operation of the vehicle but also provides a method to track the AUV navigation parameters and maneuverability. However, the seabed topography and substance have a significant influence on the detection range of underwater vehicles, which affects the accuracy of sound field prediction, target strength, and sound shadow zone location. As a result, accurate seabed exploration information often requires the submersible to operate close to the seabed. In the seabed environment, the challenges of communication and positioning come from two main aspects (Figure 5): the spatial randomness of multi-path interference caused by seabed reflection and the time

randomness brought by the time-varying complex sound propagation environment. The time–space dual randomness of the seabed environment increases the difficulty of reliable underwater communication and high-precision underwater positioning, which is also the challenge faced by subsea AUVs.

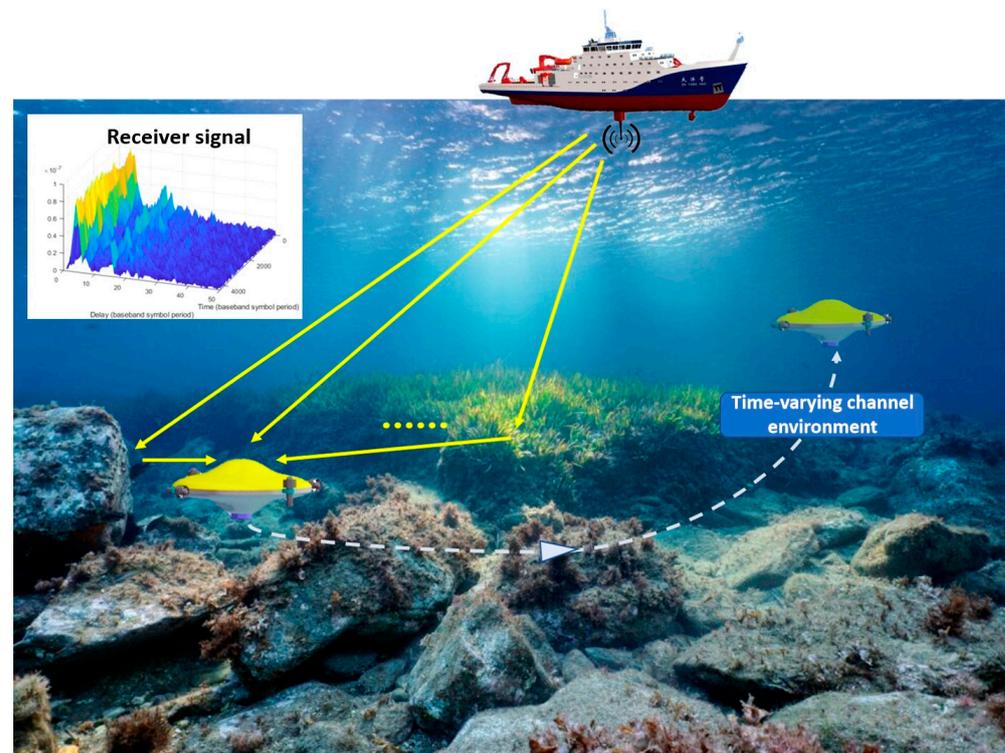


Figure 5. Schematic diagram of the impact of seabed channel environment changes on acoustic communication and positioning.

In acoustic communication systems, due to time-varying multipath expansion, frequency offset, and random phase fluctuations, near-seabed communication channels have only a few multipath components that carry important energy, and the weight coefficients of most channel responses are zero or close to zero. Therefore, a sparse multipath channel model is used for modeling. Relevant channel estimation and equalization algorithms are effective ways of dealing with multipath interference and time-varying problems in near-seabed sparse multipath channel models and improving the reliability of communication in subsea AUVs.

Due to multipath effects in acoustic positioning and navigation systems, it is very likely that reflected paths will arrive at the receiver before direct paths, making it difficult for the decision system to determine the real target, resulting in a multipath virtual source problem. This problem is particularly prominent on the seabed. In addition, when the delay of adjacent reflection paths is less than the maximum delay resolution of the positioning pulse and its processing algorithm, target ambiguity in positioning results and increased positioning errors will occur.

To overcome the multipath virtual source problem in the seabed acoustic positioning and navigation system and to further improve the positioning accuracy, researchers, in recent years, have proposed to use seabed reflection paths to obtain the propagation of the seabed communication environment and intrinsic sound lines, thereby achieving precise positioning of subsea AUVs. To accurately distinguish between direct paths and seabed reflection paths, Ahmet et al. used ray tracing to simulate complex underwater environments and studied the nearest neighbor and probability data association filter of arrival time and arrival time difference measurement models and achieved positioning and tracking of seabed AUVs [52]. By analyzing the principle of near-field positioning of horizontal

arrays, Song et al. established a mathematical model of seabed sparse multipath channels and used spatial geometric characteristics to achieve near-field positioning technology [53]. In addition, in the seabed acoustic positioning and navigation system, traditional acoustic positioning methods based on arrival time and angle do not consider seabed reflection path signals and require multiple receiving nodes to be used simultaneously to achieve positioning of seabed targets. Nevertheless, using seabed reflection path signals, it is possible to achieve positioning of seabed targets with only a single receiving node. Based on the principle of time difference of arrival positioning, Hannan et al. simultaneously used direct path signals and seabed reflection multipath signals to achieve single hydrophone positioning of deep-sea whales [54]. Sun Hua et al. studied the passive positioning of a single hydrophone for seabed targets, using the cepstrum method to estimate the multipath delay of the sea surface and seabed relative to direct waves, derived a formula for estimating the depth and distance of seabed targets through sea surface and seabed multipath delays and used measured data to verify the method [55].

Artificial intelligence technology, represented by deep learning, has recently been widely used in many fields and has achieved remarkable results, providing new ideas for solving the challenges in the above-mentioned acoustic communication positioning and navigation problems [56]. Zhang et al. proposed a neural network model that integrates acoustic OFDM demodulation, channel estimation, and equalization to achieve integration at the receiver end. The model was trained offline and tested online in a BELLHOP-based simulation channel. The results showed that the neural network-based network model has obvious advantages compared with traditional algorithms, especially in scenarios where the number of OFDM communication pilot signals is limited [57]. To alleviate the Doppler effect and multipath effect and improve communication reliability, Lee et al. proposed an acoustic receiving system based on a deep belief network. Simulation and sea trial results verified the effectiveness of this method [58]. To reduce the positioning error of the time difference of arrival acoustic sensor array positioning system, Rauchenstein et al. proposed classification and regression algorithms in machine learning to reduce errors: First, track the position of the acoustic tag through the approximate maximum likelihood algorithm. Then, filter out data points with large errors using an integrated classification tree. Simulation and experimental results show that this method has a very significant effect on reducing errors in depth [59]. Using a deep reinforcement learning algorithm, Yan et al. proposed a positioning estimator based on a deep reinforcement learning algorithm for estimating the position of underwater targets. This positioning scheme can effectively protect privacy information and has strong robustness [60]. At present, research on acoustic intelligent communication positioning and navigation technology is still in the theoretical research stage, and there is no mature application system. Therefore, it is urgent to carry out research on intelligent communication and guidance technology for subsea AUVs. It is also preferable to apply intelligent algorithms to acoustic communication positioning and navigation technology, to construct network models to simulate complex and changeable underwater environments, and to improve the reliability of communication and positioning accuracy.

The main difficulties are associated with the communication of submersibles in complex seabed environments and poor positioning accuracy due to multipath virtual sources. Thus, in order to ensure the success of underwater communication and guidance during AUV's agile operation on the seabed (such as effectively changing the height from the bottom, quickly changing the direction of navigation, etc.) as well as high-precision navigation, it is necessary to carry out in-depth research on communication theory and methods for subsea AUVs, joint channel estimation and equalization algorithms adapted to seabed sparse channels, and integrated communication positioning theory based on broadband communication signal reuse. Subsea AUVs should be enabled to have multipath resistance and noise resistance in complex underwater environments, as well as to possess higher positioning frequency and accuracy to meet the needs of underwater acoustic communication and navigation positioning for underwater AUV operations. Meanwhile, the navigation method of inertial navigation combined with DVL and the navigation positioning method

of seabed terrain matching provides more potential positioning and navigation solutions for subsea AUVs.

5. Wireless Power/Data Transmission Technology

Due to the increase in operation time and range on the seabed, the amount of stored energy has become a limiting factor in terms of mission length and intensive task performance. Wireless power transfer (WPT) provides a contactless way for energy delivery. Due to electrical isolation between the primary and secondary sides, the danger of electric leakage in wet plugs can be avoided. The underwater wireless power transfer technology greatly facilitates several important applications, including deep sea submersibles, oil rigs, and mining operations. The major concerns of underwater wireless power transfer include attenuation in seawater, extreme temperature and pressure conditions, disturbance of ocean currents, and bio-security.

MIT and WHOI pioneered the idea of applying wireless charging to the underwater vehicle in the submarine sampling network AOSN. In 2001, Feezor and Sorrell developed an underwater wireless charging system in which the underwater robot MIT/WHOI Odyssey II is charged at a seafloor base wirelessly (Figure 6). The system works in the 1000 m deep ocean and transfers 200 W power with 79% efficiency [61,62]. Soon afterward, Underwater Vehicle REMUS 100, REMUS 600, and Bluefin 21 all accomplished underwater wireless charging experiments [63,64]. The charging platform for REMUS 100 and Bluefin 21 is shown in Figure 6. The Kawasaki shipbuilding company belonging to Kawasaki Heavy Industries designed a UUV named “Marine Bird”. When the UUV docks in the underwater platform, the underwater base station provides power to the UUV using an electromagnetic induction principle [65,66]. In 2004, Tohoku University and NEC company jointly developed a contactless charging system for AUVs, as shown in Figure 6. The system can transfer 500 W of power with 90% efficiency; meanwhile, the system is stable and not vulnerable to disturbance [67].

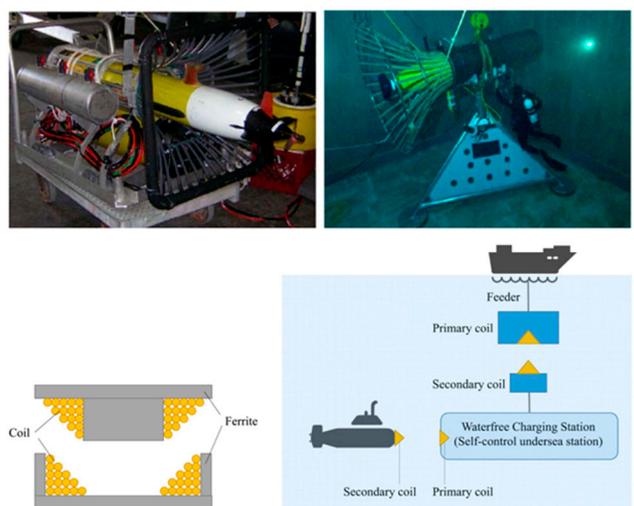


Figure 6. Photograph of the AUV and docking station [61,65,66].

6. A Practical Example of Subsea AUV: Autonomous Underwater Helicopter

Inspired by the benthic creature, the stingray, Zhejiang University proposed a seabed-resident AUV platform solution—the Autonomous Underwater Helicopter (AUH)—in 2015. The AUH has a disc-shaped body structure and can take off and land on the seabed and is also capable of all-round steering and fixed-point hovering. It is designed to operate stably on the seafloor and effectively fills the gap in the observation platforms in the ocean bottom area. The AUH works in coordination with the Underwater Helipad [68] (Figure 7), which provides power supply and information transmission for the AUH, enabling the AUH to remain underwater for long periods (Subsea Residency). With support from

national and local scientific research groups, the research team has carried out preliminary applications in seabed observation and detection. In terms of acoustic communication, the maximum distance for noncoherent uplink and downlink is 5 km and the maximum distance for coherent uplink and downlink is 3 km. The effective distance for positioning is 5 km and the error is less than or equal to 0.25% of the distance (which is at the leading level compared with existing technologies). The group is determined to focus on the study of the mobility and agility of subsea AUVs in the next few years in order to further enhance their agility when operating in complex seabed environments and to better perform large-scale and long-term observation and detection.

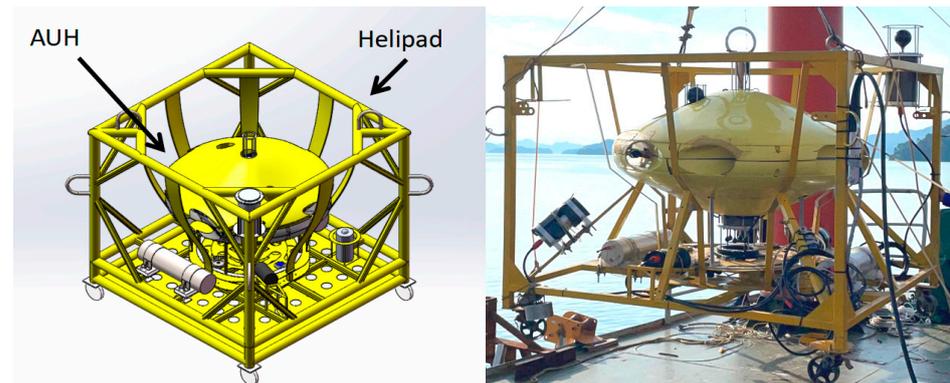


Figure 7. AUH and Helipad.

During the overall design of AUH, emphasis was placed on adapting to the needs of underwater operations. Compared with conventional torpedo-shaped AUVs, the AUH has unparalleled advantages in terms of bottom altitude, hovering, rapid turning, and underwater takeoff and landing. In addition, the disk-shaped AUH is more conducive to maintaining stability during underwater operations, making it easier to achieve maneuverability such as near-bottom navigation, hovering at fixed points, and vertical takeoff and landing. It is worth pointing out that the economic cruising speed of AUH is not high—generally not greater than 2 knots—and can be differentiated from torpedo-shaped AUVs.

Seafloor observation and exploration place high demands on the maneuverability and agility of subsea AUVs. In terms of the agility movement mechanism, early-stage research was carried out on its maneuverability, taking into account the hydrodynamic characteristics of the circular disc-shaped AUH [48–51,69,70] and optimizing the horizontal and vertical maneuvering performance of AUH through shape iteration. In view of the problem that its heading is vulnerable to external disturbance and model mismatch, the model-free parameter adaptive sliding mode control method [71] of the underwater helicopter was studied to better realize free takeoff and landing, fixed-point hovering, full-circle steering, and other functions. At the same time, initial consideration was given to agility in terms of full-circle steering. AUH has faster adjustment speed in degrees of freedom such as heading, roll, and pitch and can complete iconic agile actions such as zero-radius full-circle rotation.

In response to various needs such as seabed environment exploration, water quality monitoring, and ecological protection, and after years of iteration, Zhejiang University's team developed a series of AUH prototypes (Figure 8) for different application scenarios. Mini-AUH is the first-generation concept prototype used to verify the basic movement functions of disc-shaped submersibles. Subsequently, an S-AUH with an acoustic positioning function was developed. The diameter of the S-AUH is 0.8 m. It has vectoring propulsion and is equipped with an ultra-short baseline positioning function. Under the support of National Key R&D programs, G-AUH, which has functions such as acoustic communication guidance, buoyancy adjustment, and wireless charging was developed and completed sea trials at a depth of 1000 m in the South China Sea. Since 2019, the research team has embarked on a series of productization paths for AUHs, including ICE-AUH

for under-ice algae observation, CORAL-AUH for coral reef ecological observation, and standardized product prototypes OT-AUH for various industrial needs.

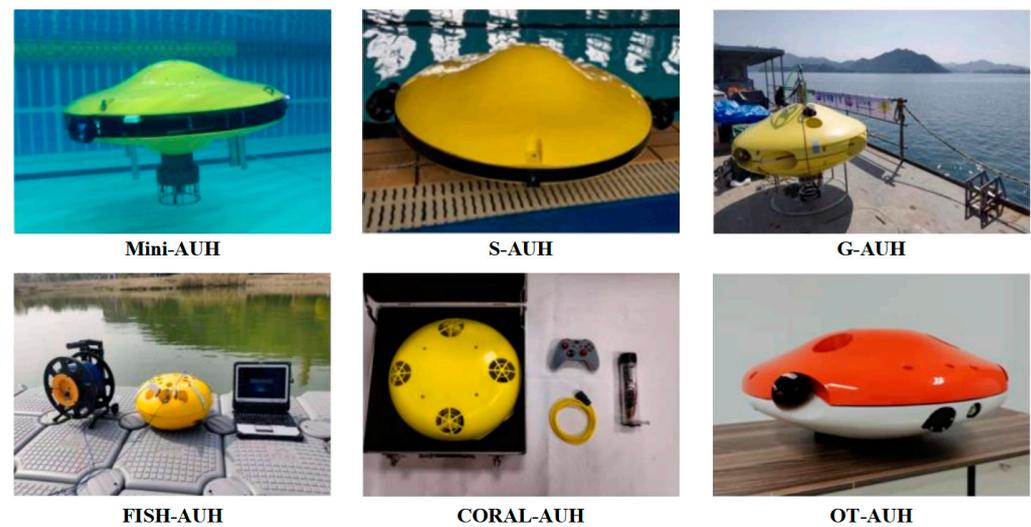


Figure 8. Development and Evolution of AUH Series Prototypes.

7. Conclusions

In terms of seabed observation and detection, various existing traditional methods are limited by their technical features and thus cannot efficiently nor comprehensively conduct observation and detection of seabed environments. Thus, there is an urgent need to develop an AUV capable of performing seabed observation and detection operations. Subsea AUVs, which operate for long-term periods on the seabed, need to meet three technical requirements: (1) a structure suitable for seabed residency, (2) strong agility, and (3) solve the problem of acoustic communication and navigation in complex seabed environments. This paper reviewed the development and evolution of subsea AUVs, analyzed the difficulties and solutions of seabed acoustic communication and positioning navigation technology, and studied the key technologies of agile movement of subsea AUVs. Additionally, there are two key points in the study of subsea AUVs: an agile movement model based on hydrodynamics and a control mechanism supported by high anti-noise acoustic navigation. Subsequently, taking the disc-shaped AUH as an example, this paper introduced a solution for subsea AUVs. Subsea AUVs are capable of efficiently and continuously collecting accurate high-resolution data for an extended period without the need for collection and recovery. However, the lack of human intervention may lead to errors in data processing and interpretation. With the increasing requirement for seabed operations, the development of subsea AUVs and the comprehensive improvement of their seabed observation and detection capabilities will provide solutions for scientific and engineering problems such as scientific exploration, marine resource exploration, and seabed target discovery.

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