Engineering 25 (2023) 21–27

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Views & Comments

AUH, a New Technology for Ocean Exploration

Jing Zhou [a,b], Haocai Huang [a,c], S.H. Huang [a,c], Yulin Si [a,c], Kai Shi [e], Xiangqian Quan [f], Chunlei Guo [e], Chen-Wei Chen [a,c], Zhikun Wang [a,c], Yingqiang Wang [a,c], Zhanglin Wang [a,c], Chengye Cai [a,c], Ruoyu Hu [a,c], Zhenwei Rong [a,c], Jiazhong He [a,b], Ming Liu [a,c], Ying Chen [a,c,d]

[a] *Intelligent Ocean Technology Center, Zhejiang University, Zhoushan 316021, China*
[b] *College of Electrical Engineering, Zhejiang University, Hangzhou 310027, China*
[c] *Ocean College, Zhejiang University, Zhoushan 316021, China*
[d] *State Key Laboratory of Fluid Power & Mechatronic Systems, Zhejiang University, Hangzhou 310027, China*
[e] *State Key Laboratory of Robotics, Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang 110169, China*
[f] *Institute of Deep-Sea Science and Engineering, Chinese Academy of Sciences, Sanya 572000, China*

The demand for ocean exploration down to the deep seafloor, for instance, ocean resource exploration and ocean observations, has promoted innovations in underwater technology. Underwater unmanned vehicles are urgently required to be deployed and operate on the seafloor. Because most underwater vehicles are unable to operate on the seafloor and even have difficulty reaching there, we developed a seafloor-resident autonomous underwater helicopter (AUH). This paper introduces the new idea and design of AUHs and discusses the pros and cons of AUHs in comparison with other underwater vehicles. Afterwards, we verify the importance of developing new facilities to enable mankind to easily operate close to the seafloor.

1. Deep seafloor exploration

Most ocean resources are on the seafloor, such as deep-sea manganese nodules, cobalt-rich crust, and hydrothermal sulphide. The seafloor is the major area for marine science observation [1–6], and many artificial constructions built on the seafloor need to be monitored and maintained. For instance, the long-term and slow growth patterns of deep-sea organisms surrounding hydrothermal vent areas need to be observed and monitored with resident vehicles [7]. In addition, supervising the seafloor also attracts much attention from military forces.

Until now, there have been very few means to help mankind reach the seafloor due to various technological difficulties [6,8]. Underwater unmanned vehicles are major tools used for underwater exploration (Fig. 1), such as autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), and sea gliders, which extend the range of human exploration into unknown regions unreachable before. AUV mobility is not restricted by umbilical cables; however, their torpedo shape and underactuation characteristics make them easily trapped near the sea bottom. ROVs are, in essence, underactuated systems, so their dirigibility is lacking, especially in complicated terrain. Umbilical cables connected to a deck control station further reduce the mobility of ROVs within a restricted space. A deep-sea submersible vehicle (DSV) can bring mankind to the seafloor, but usually the working area is greatly limited. In situations with complicated terrain or navigation in narrow spaces, traditional underwater vehicles encounter large practical limitations.

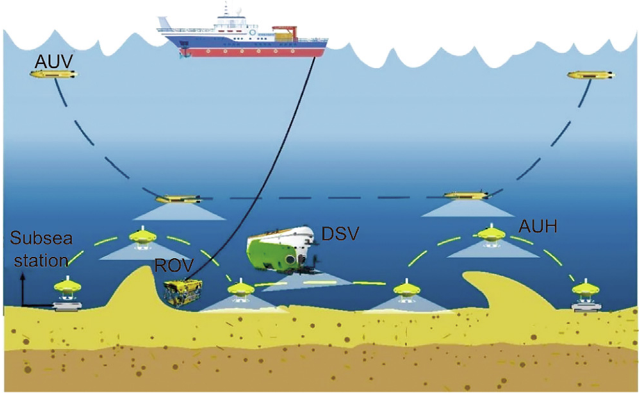


Fig. 1. Various underwater unmanned vehicles in a water column. AUV: autonomous underwater vehicle; ROV: remotely operated vehicle; DSV: deep-sea submersible vehicle.

With the development of ocean equipment and technology, underwater vehicles are taking on increasingly new forms (Fig. 2). Submarine wheeled vehicles (i.e., crawlers), move directly on the seafloor and have been widely applied to long-term monitoring [9,10] and deep-sea sampling [11]. Wheeled vehicles always have low gravity, which restricts their mobility [12]. Several underwater vehicles use bioinspired structures, and locomotion systems [13], mimicking fish [14–18], mantas [19–21], octopi [22,23], and crabs [24] have been developed.

https://doi.org/10.1016/j.eng.2022.09.007

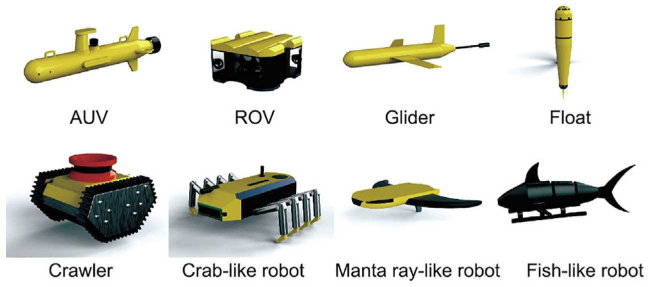


Fig. 2. The variety of underwater unmanned vehicles.

Closeup exploration of the seafloor requires new forms of underwater vehicles that are capable of taking off and landing on the seafloor, hovering at any altitude [25]. Existing underwater vehicle prototypes can rarely provide an adequate platform for *in situ* close exploration and large-scale observation on the seafloor. The challenges mainly lie in three aspects: ① The underwater vehicle has to adjust its posture and direction in an ultraflexible way to explore the complicated seafloor environment; ② to avoid emerging from the sea surface too frequently, it has to perform power recharging and data transmission on the seafloor; and ③ it has to be able to navigate in a weak communication environment and complete accurate docking to a sub-station which the vehicle can be electrically charged to get power and connected.

We sought to build and successfully deploy an underwater vehicle that can autonomously cruise close to the seafloor. ① The seafloor-resident working mode proposes special requirements for its contour design. On one hand, the underwater vehicle needs to maneuver in any direction in the horizontal plane close to the seabed; on the other hand, the underwater vehicle needs to navigate in a large range, so it needs a revolving body structure and a streamline profile in the horizontal direction to reduce drag force. ② The novel vehicle is designed to be supported by the base station on seafloor, which supplies power and data transmission. ③ Acoustic–optic navigation is utilized to ensure successful docking into the base station.

2. The AUH, a new member of the AUV family

2.1. New concept proposal

Inspired by bottom-dwelling stingrays, we developed a disc-shaped seafloor-resident underwater vehicle, an AUH (Fig. 3), which can take off and land on the seafloor and hover at any altitude. It can be equipped with cameras and sensors for scientific surveys, even with one or two manipulators to perform work if necessary. The AUH can either work in AUV mode or work collaboratively with underwater helipads. Underwater navigation is completed using a passive inverted ultrashort baseline (piUSBL) supplemented by an inertial measurement unit (IMU), and the path is adjusted according to real-time sensing information and the geographic location. An underwater acoustic communication mode is utilized between different AUHs for network communication.

The endurance of mission autonomy is an important challenge in the design of a self-contained underwater vehicle. The use of submerged docking stations permits battery recharging and data upload/download, which provides a method to lengthen the operation hours of underwater vehicles without compromising propulsion and payload power budgets [26–30]. Autonomous underwater docking is, however, complicated by the presence of currents and obstacles in the water and by the relative dynamic differences in orientation between the dock and vehicle. A robust docking guidance system is therefore a core and crucial component for ensuring successful underwater vehicle docking. The docking base of the AUH is a helipad, as shown in Fig. 4.

According to the cooperation mode between the AUH and helipad, the system operates under three scenarios: ① The helipad is connected to a seafloor observatory, and the AUH operates as a mobile platform in the network; ② a mother ship lays out the helipad through a photoelectric composite cable, and the AUH performs seafloor operation with the support of the helipad; and ③ the AUH works in AUV mode without the helipad. These three scenarios can be changed according to on-site requirements.

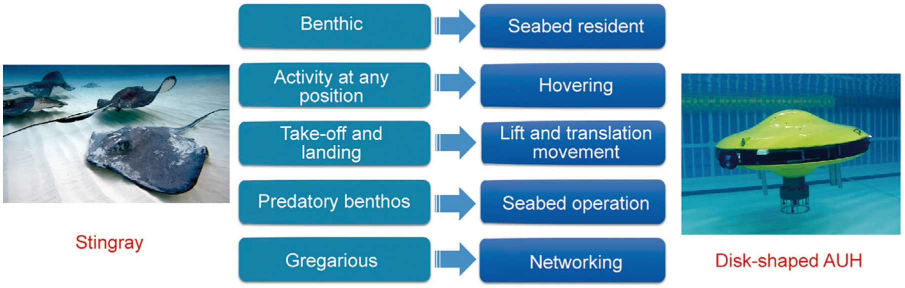


Fig. 3. The AUH idea was inspired by stingrays.

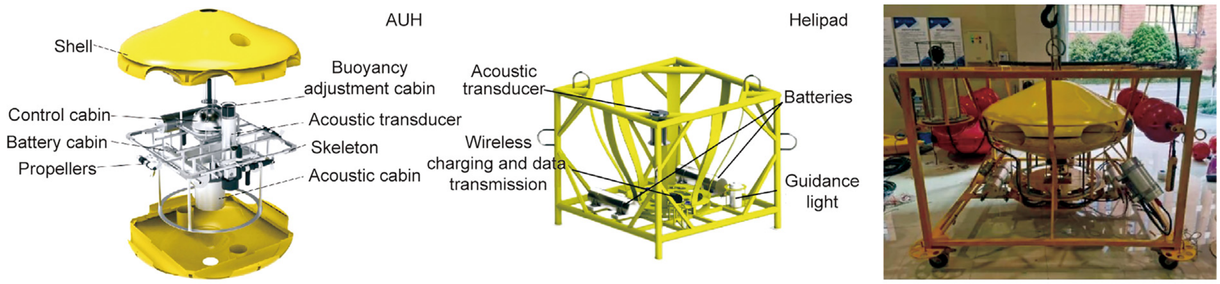


Fig. 4. An AUH and its helipad.

2.2. Development of the AUH spectrum

Building on previous experience, we developed a series of AUH prototypes [31–37] and have begun the productization process. Equipped with various types of detection equipment, an AUH can evolve for different application scenarios. The development and evolution of the AUH family is shown in Fig. 5, in which the number indicates the start-up year of the prototype. The mini-AUH is the first-generation conceptual prototype, with four horizontal propellers and an optical positioning system, and it verifies the basic motions of a disc-shaped AUH. Based on the concept of the mini-AUH, we developed an S-AUH with a simple acoustic positioning system that is 1 m in diameter to further investigate the hydrodynamic characteristics and hovering performance. Under the sponsorship of the National Key Research and Development Project, we designed and developed a G-AUH with more comprehensive functions, such as acoustic positioning, buoyancy regulation, wireless charging, and docking with the helipad under acoustic/optic guidance. The G-AUH was designed to withstand a 1000 m depth under the sea and was tested in Qiandaohu Lake and in the South China Sea. In 2019, we started the customized development of AUHs for different application scenarios. The ICE-AUH was designed for the observation of algae under arctic ice. Equipped with an acoustic positioning system, the ICE-AUH was able to complete polar coordinate positioning with a beacon as the center. The CORAL-AUH was designed for ecological observation of coral reefs, equipped with a high definition (HD) camera, as well as a variety of sensors, such as a chlorophyll meter, salinity meter, pH meter, turbidity meter, and dissolved oxygen concentration meter. The OT-AUH is an engineering prototype developed in cooperation with Zhejiang OceanTech Company, and it was designed as a standard product for various industrial applications. A detailed comparison of the sensor assets and functions can be found in MethodsX in Appendix A.

3. AUH implementation

3.1. System integration

The AUH system is composed of the AUH, console, and helipad (Fig. 6). An AUH is further divided into the supporting structure and the following modules: communication, control, driver, operation, navigation, and auxiliary (with rechargeable batteries providing power to all units through an energy management system).

The detailed structural composition is shown in Fig. 4. The shell of an AUH is a thin shell roughly in the shape of a circular disc, which is mainly used to protect the internal components of the AUH from the damaging impact of the water flow, as well as to provide a shape with excellent hydrodynamic performance. The skeleton is an important structure for bearing and fixing the pressure cabin, propeller, sensor, and other parts within the AUH. The pressure cabin provides protection for the control system hardware and batteries, buoyancy adjustment devices and related components. Buoyancy materials are used to compensate for the negative buoyancy of the AUH body in water. The driver module is composed of two vertical propellers, two horizontal propellers, a buoyancy adjustment system, and a gravity adjustment system.

The AUH utilizes an acoustic and optic combined navigation scheme (Fig. 7). At a distance, the AUH determines its position with an acoustic transducer and navigates towards the helipad. Upon approaching the helipad, the AUH gradually adjusts its posture to align with the target orientation. Closer in, the AUH tracks the navigation lights with a machine vision algorithm to adjust its position and posture precisely and dock with the helipad successfully (MethodsX for details on docking).

The uniqueness of the acoustic positioning system of the AUH is further illustrated in Fig. 8. Unlike a conventional ultra-short baseline (USBL) positioning system with a transceiver mounted under a mother ship and a responder on a subsea target [38], our piUSBL system consists of a single acoustic beacon placed on a mother ship or a subsea station and a passive receiving array on the moving AUH. The advantage of the piUSBL positioning system mainly lies in the following three aspects [39–42]: ① The piUSBL system features low cost, low power, and light weight; ② the underwater vehicle is able to obtain instantaneous acoustic measurements without waiting for topside measurements through acoustic communication equipment, as in a conventional USBL system; and ③ the omnidirectional positioning pulses from the beacon enable passive receivers on multiple vehicles to self-locate and navigate concurrently, which is of great significance to multivehicle applications. A detailed explanation of the piUSBL system can be found in MethodsX.

3.2. Field test

After a series of preliminary tests in pools and lakes, a sea trial was conducted in the South China Sea. The deployment of the AUH is shown in Fig. 9. The objective of the sea trial was to test the operation of the AUH, such as mobility and navigation capability. It was necessary that the AUH could complete mobility tests, such as moving straight forward, circular steering, fixed-point hovering, floating and sinking, and landing on and taking off from the helipad under piUSBL and acoustic–optic combined navigation. The operating state of the helipad can be clearly seen on a console onboard the mother ship, as shown in Fig. 10.

In the sea trial, the AUH successfully docked to the helipad twice under acoustic–optic navigation and conducted wireless charging with the helipad. Experiments validated that the helipad

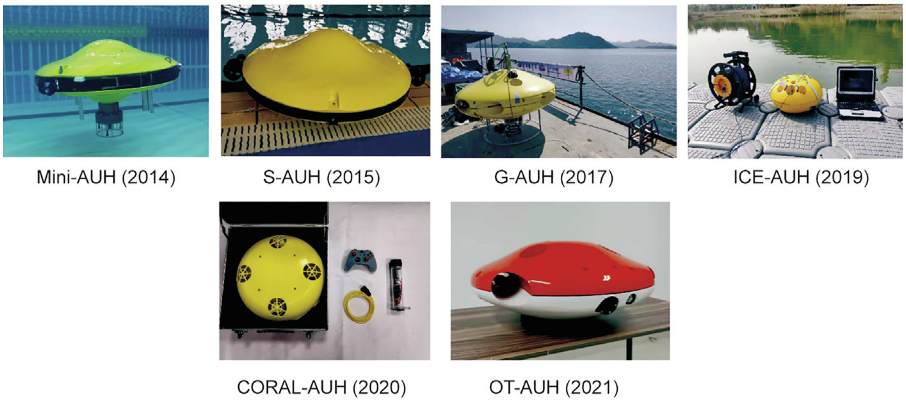

Mini-AUH (2014)
S-AUH (2015)
G-AUH (2017)
ICE-AUH (2019)
CORAL-AUH (2020)
OT-AUH (2021)

Fig. 5. Development and evolution of the AUH models.

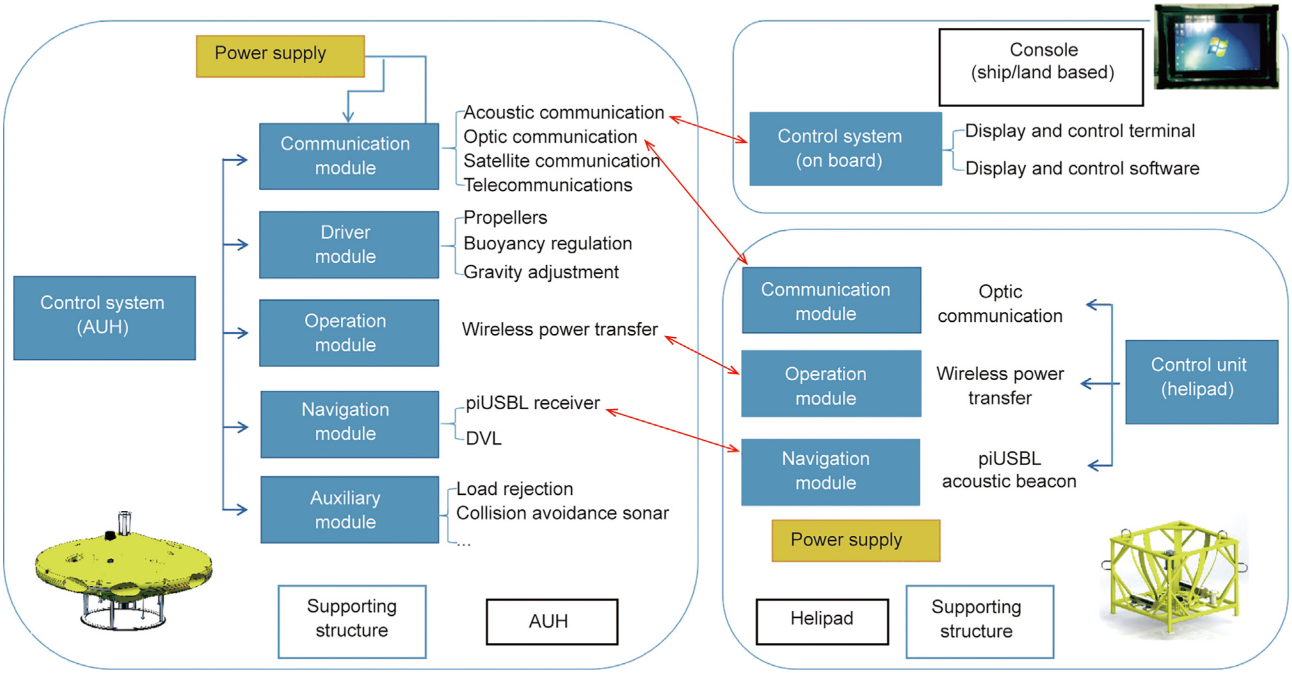


Fig. 6. System architecture. DVL: Doppler velocity log.

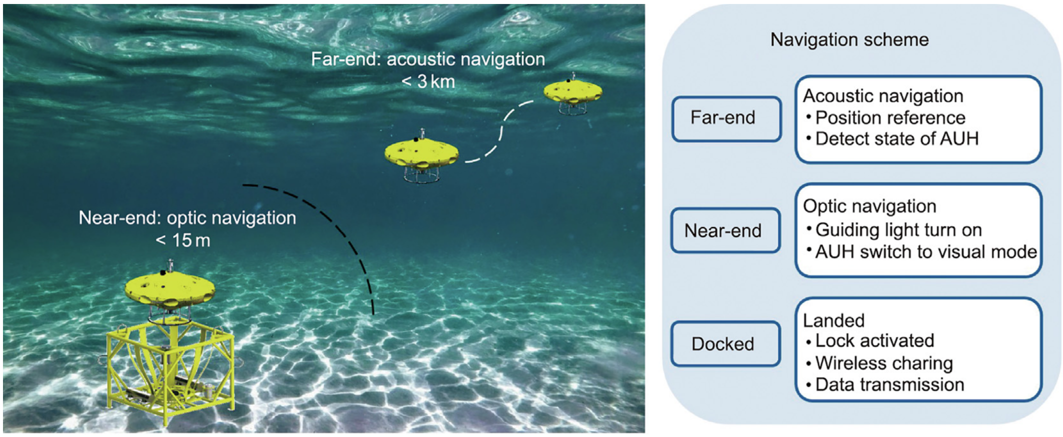


Fig. 7. Acoustic–optic combined navigation scheme.

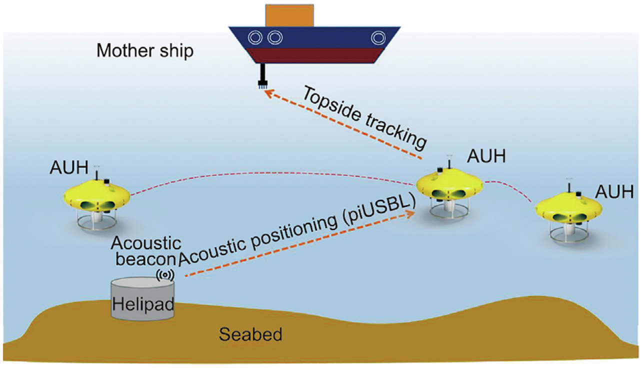


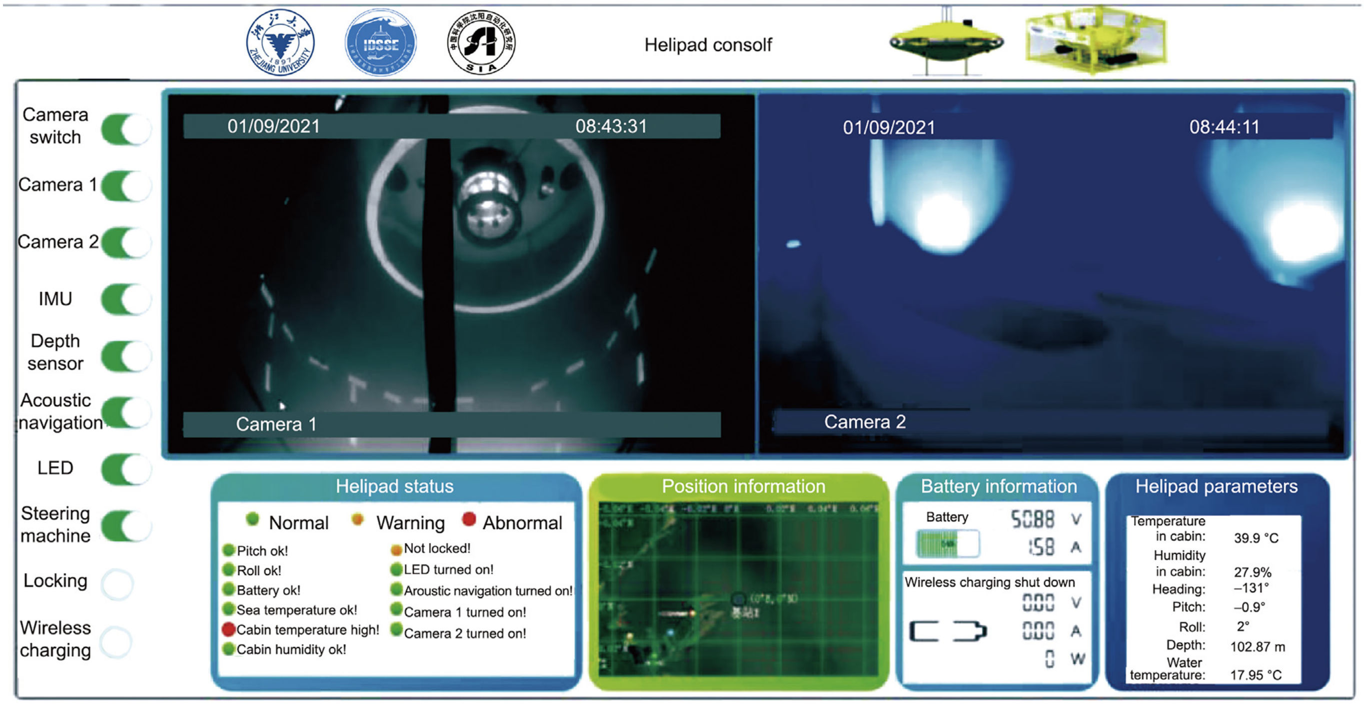
Fig. 8. Operation of an AUH and its helipad (when the AUH is tested in a sea trial).

is an important platform for the AUH on the seafloor and guarantees the safe housing and reliable operation of the AUH. A comprehensive test was carried out on cruising near the seafloor, landing on and taking off from the helipad, and all-round steering, fixed-point hovering, wireless charging, and acoustic navigation and tracking functions. The new AUH underwater vehicle concept meets the preset missions and has been proven to be novel and reliable (MethodsX).

Fig. 9. Deployment of the AUH for the sea trial.

4. Perspectives

A new form of seafloor-resident underwater vehicle is proposed in this paper, the AUH, which can take off and land on the seafloor



● Normal ● Warning ● Abnormal

● Pitch ok!
● Roll ok!
● Battery ok!
● Sea temperature ok!
● Cabin temperature high!
● Cabin humidity ok!
● Not locked!
● LED turned on!
● Aroustic navigation turned on!
● Camera 1 turned on!
● Camera 2 turned on!

Battery 5088 V
158 A

Wireless charging shut down
000 V
000 A
0 W

Temperature in cabin: 39.9 °C
Humidity in cabin: 27.9%
Heading: –131°
Pitch: –0.9°
Roll: 2°
Depth: 102.87 m
Water temperature: 17.95 °C

Fig. 10. Master control console onboard the mother ship. LED: light-emitting diode.

and hover at fixed points. It can dive close to the seafloor and observe it clearly equipped with cameras and sensors for scientific surveys. In addition, collaborating with underwater helipads, the AUH can remain on the seafloor for a long period by receiving power recharging and data connection. Different from other persistent underwater vehicles, the AUH cruises in a flexible trajectory, which makes it an ideal platform for fine exploration of the seafloor over a vast range. As a result, the AUH can routinely operate throughout the deep ocean as an important supplement to existing cabled observation networks [43], which is crucial to support next-generation studies of deep ocean processes on the seafloor that are otherwise beyond our operational reach.

On the other hand, the disadvantages of AUHs are also apparent: A larger cross-sectional area of the body results in greater resistance (MethodsX), which makes it difficult for AUHs to cruise underwater quickly or travel long distances. Additionally, without manual auxiliary operation under umbilical cables, neither AUVs nor AUHs can perform delicate underwater operations such as grasping with manipulators. Due to the limitation of experimental conditions, experiments such as long-time endurance on the seafloor with the assistance of the helipad and collaboration between multiple AUHs were not performed at the current stage.

Overall, AUHs have their own unique characteristics, making them very suitable for certain dedicated scenarios. A comprehensive comparison of an AUH with other underwater vehicles, ROVs, and torpedo-type traditional AUVs, is shown in Table 1. It is clear how AUHs should be improved urgently and where they are suitable for the usage.

5. Conclusions

To summarize, this paper contributes to the field of undersea vehicles that can survive in the deep ocean and serve as a platform for the exploration on the seafloor. We present a stingray-shaped underwater vehicle, alongside an underwater helipad, that can complete scientific surveys continuously within certain sea areas. Specifically, the contributions of this work include the first AUH prototype capable of ① performing spin turns, performing vertical rotations, hovering, free landing on the seafloor, and take-off from the seafloor; ② performing wireless power charging and data transmission via an underwater helipad; and ③ precisely docking with the helipad via an acoustic–optical navigation system. As a new category of underwater vehicles, AUHs are a new concept for the world of ocean technology. Incremental technological steps towards realizing AUHs will yield revolutionary scientific and operational value.

There are some outlooks we developed in our recent research.

(1) Traditional ocean science and technology research uses ships, satellites, submersibles, buoys, cycling floats, gliders, and

Table 1
Pros and cons of an AUH compared with other underwater vehicles.

Underwater vehicles	Pros						Cons	
	Mobile observation	360° steering	Hovering at fixed point	Near seafloor operation	Heavy payload	Long endurance	Delicate manipulation	Long-range movement
AUH	Yes	Yes	Yes	Yes	Yes	No	No	No
Traditional AUV	Yes	No	No	No	No	Yes	No	Yes
ROV	No	Yes	Yes	No	Yes	Yes	Yes	No
Crawler	No	No	Yes	Yes	Yes	Yes	Yes	No
Bionics	Yes	Yes	No	Yes	No	No	No	No

autonomous vehicles to explore the ocean, yet, the sea bottom cannot be easily accessed, mainly due to the limitations of existing underwater platforms. Cable observation sites provide long-term and real-time monitoring on fixed sites. On the other hand, AUVs serve as mobile observation platforms, which are an effective supplement to fixed sites.

(2) The development of the AUH fills the gap in seafloor residential vehicles, which is of vital significance for deep-sea exploration. AUH research greatly expands the theoretical system of AUVs. The name AUH is a new term we contribute to ocean technology, which is beginning to be used frequently in some major journals of ocean science and technology.

(3) A group of academic and industry applications are pieces of evidence that AUHs have made persistent vehicular operations in the ocean, especially on the seafloor, a feasible step. However, it will require more attention and further research in aspects of hydrodynamic optimization, resistance reduction, precious navigation near the seafloor, *in situ* energy generation for the helipad, and so forth.

(4) To improve the AUH in depth, related technologies need to be developed and perfected, including high precision sensors, acoustic communication, navigation near the sea bottom, and autonomy algorithms.

(5) Successfully developing the AUH will face surmounting technical, financial, and operational challenges. The effort must be guided by one or more visionary goals, and backed by a strong financial commitment. Nevertheless, the development of the AUH makes the pursuit of enhanced human–ocean interactions becoming an increasingly achievable goal; and the potential to enhance the geophysical, geochemical, and biological understanding of the sea bottom will become a powerful justification and a definable milestone.

Acknowledgments

The authors acknowledge the financial support from the State Key Research and Development Project (2017YFC0306100), Hainan Key Research and Development Project (ZDYF2020197), and Fundamental Research Funds for the Zhejiang Provincial Universities (2021XZZX014).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2022.09.007.

References

[1] Danovaro R, Aguzzi J, Fanelli E, Billett D, Gjerde K, Jamieson A, et al. An ecosystem-based deep-ocean strategy. Science 2017;355(6324):452–4.
[2] Chatzievangelou D, Bahamon N, Martini S, del Rio J, Riccobene G, Tangherlini M, et al. Integrating diel vertical migrations of bioluminescent deep scattering layers into monitoring programs. Front Mar Sci 2021;8:661809.
[3] Chatzievangelou D, Aguzzi J, Scherwath M, Thomsen L. Quality control and pre-analysis treatment of the environmental datasets collected by an internet operated deep-sea crawler during its entire seven-year long deployment (2009–2016). Sensors 2020;20(10):2991.
[4] Rountree RA, Aguzzi J, Marini S, Fanelli E, De Leo FC, Del Rio J, et al. Towards an optimal design for ecosystem-level ocean observatories. In: Hawkins SJ, Allcock AL, Bates AE, Evans AJ, Firth LB, McQuaid CD, et al., editors. Oceanography and marine biology: an annual review. Boca Raton: CRC Press; 2020. p. 79–106.
[5] Aguzzi J, Chatzievangelou D, Marini S, Fanelli E, Danovaro R, Flögel S, et al. New high-tech flexible networks for the monitoring of deep-sea ecosystems. Environ Sci Technol 2019;53(12):6616–31.
[6] Wynn RB, Huvenne VAI, Le Bas TP, Murton BJ, Connelly DP, Bett BJ, et al. Autonomous underwater vehicles (AUVs): their past, present and future contributions to the advancement of marine geoscience. Mar Geol 2014;352:451–68.
[7] Juniper SK, Thornborough K, Douglas K, Hillier J. Remote monitoring of a deep-sea marine protected area: the Endeavour Hydrothermal Vents. Aquat Conserv Mar Freshwater Ecosyst 2019;29(S2):84–102.
[8] Bogue R. Underwater robots: a review of technologies and applications. Ind Rob 2015;42(3):186–91.
[9] Doya C, Chatzievangelou D, Bahamon N, Purser A, De Leo FC, Juniper SK, et al. Seasonal monitoring of deep-sea megabenthos in Barkley Canyon cold seep by internet operated vehicle (IOV). PLoS ONE 2017;12(5):e0176917.
[10] Laschi C, Mazzolai B, Cianchetti M. Soft robotics: technologies and systems pushing the boundaries of robot abilities. Sci Rob 2016;1(1):eaah3690.
[11] Yoshida H, Aoki T, Osawa H, Ishibashi S, Watanabe Y, Tahara J, et al. A deepest depth ROV for sediment sampling and its sea trial result. In: Proceedings of 2007 Symposium on Underwater Technology and Workshop on Scientific Use of Submarine Cables and Related Technologies; 2007 Apr 17–20; Tokyo, Japan. IEEE; 2007. p. 28–33.
[12] Inoue T, Shiosawa T, Takagi K. Dynamic analysis of motion of crawler-type remotely operated vehicles. IEEE J Oceanic Eng 2013;38(2):375–82.
[13] Aguzzi J, Costa C, Calisti M, Funari V, Stefanni S, Danovaro R, et al. Research trends and future perspectives in marine biomimicking robotics. Sensors 2021;21(11):3778.
[14] Marras S, Porfiri M. Fish and robots swimming together: attraction towards the robot demands biomimetic locomotion. J R Soc Interface 2012;9(73):1856–68.
[15] Marchese AD, Onal CD, Rus D. Autonomous soft robotic fish capable of escape maneuvers using fluidic elastomer actuators. Soft Rob 2014;1(1):75–87.
[16] Katzschmann RK, Marchese AD, Rus D. Hydraulic autonomous soft robotic fish for 3D swimming. In: Hsieh MA, Khatib O, Kumar V, editors. Experimental robotics: the 14th international symposium on experimental robotics. Cham: Springer; 2015. p. 405–20.
[17] Marchese AD, Onal CD, Rus D. Towards a self-contained soft robotic fish: on-board pressure generation and embedded electro-permanent magnet valves. In: Desai JP, Dudek G, Khatib O, Kumar V, editors. Experimental robotics: the 13th international symposium on experimental robotics. Heidelberg: Springer; 2013. p. 41–54.
[18] Phamduy P, Vazquez M, Rizzo A, Porfiri M. Miniature underwater robotic fish for animal–robot interactions. In: Proceedings of the ASME 2016 Dynamic Systems and Control Conference; 2016 Oct 12–14; Minneapolis, MN, USA. ASME; 2016. p. V002T17A009.
[19] Suzumori K, Endo S, Kanda T, Kato N, Suzuki H. A bending pneumatic rubber actuator realizing soft-bodied manta swimming robot. In: Proceedings of 2007 IEEE International Conference on Robotics and Automation; 2007 Apr 10–14; Rome, Italy. IEEE; 2007. p. 4975–80.
[20] Cloitre A, Arensen B, Patrikalakis NM, Youcef-Toumi K, Alvarado PVY. Propulsive performance of an underwater soft biomimetic batoid robot. In: Proceedings of the Twenty-Fourth International Ocean and Polar Engineering Conference; 2014 Jun 15–20; Busan, Republic of Korea. Mountain View: ISOPE; 2014. 326–33.
[21] Li T, Li G, Liang Y, Cheng T, Dai J, Yang X, et al. Fast-moving soft electronic fish. Sci Adv 2017;3(4):e1602045.
[22] Calisti M, Giorelli M, Levy G, Mazzolai B, Hochner B, Laschi C, et al. An octopus-bioinspired solution to movement and manipulation for soft robots. Bioinspir Biomim 2011;6(3):036002.
[23] Purser A, Thomsen L, Barnes C, Best M, Chapman R, Hofbauer M, et al. Temporal and spatial benthic data collection via an internet operated deep sea crawler. Methods Oceanogr 2013;5:1–18.
[24] Picardi G, Chellapurath M, Iacoponi S, Stefanni S, Laschi C, Calisti M. Bioinspired underwater legged robot for seabed exploration with low environmental disturbance. Sci Rob 2020;5(42):eaaz1012.
[25] Aguzzi J, Flögel S, Marini S, Thomsen L, Albiez J, Weiss P, et al. Developing technological synergies between deep-sea and space research. Sci Anthropocene 2022;10(1):00064.
[26] Singh H, Bellingham JG, Hover F, Lemer S, Moran BA, von der Heydt K, et al. Docking for an autonomous ocean sampling network. IEEE J Oceanic Eng 2001;26(4):498–514.
[27] Kawasaki T, Fukasawa T, Noguchi T, Baino M. Development of AUV "Marine Bird" with underwater docking and recharging system. In: Proceedings of 2003 International Conference Physics and Control; 2003 Jun 25–27; Tokyo, Japan. IEEE; 2003. p. 166–70.
[28] Shi JG, Li DJ, Yang CJ. Design and analysis of an underwater inductive coupling power transfer system for autonomous underwater vehicle docking applications. J Zhejiang Univ-Sci C 2014;15(1):51–62.
[29] Zhang T, Li DJ, Yang CJ. Study on impact process of AUV underwater docking with a cone-shaped dock. Ocean Eng 2017;130:176–87.
[30] Zheng R, Song T, Sun QG, Guo JQ. Review on underwater docking technology of AUV. Chin J Ship Res 2018;13(6):30–7.
[31] Chen CW, Yan NM. Prediction of added mass for an autonomous underwater vehicle moving near sea bottom using panel method. In: Proceedings of the 4th International Conference on Information Science and Control Engineering (ICISCE); 2017 Jul 21–23; Changsha, China. IEEE; 2017. p. 1094–8.
[32] Chen CW, Yan NM, Leng JX, Chen Y. Numerical analysis of second-order wave forces acting on an autonomous underwater helicopter using panel method. In: Proceedings of OCEANS 2017-Anchorage; 2017 Sep 18–21; Anchorage, AK, USA. IEEE; 2017. p. 1–6.
[33] Chen CW, Jiang Y, Huang HC, Ji DX, Sun GQ, Yu Z, et al. Computational fluid dynamics study of the motion stability of an autonomous underwater helicopter. Ocean Eng 2017;143:227–39.
[34] An X, Chen Y, Huang H. Parametric design and optimization of the profile of autonomous underwater helicopter based on NURBS. J Mar Sci Eng 2021;9(6):668.

[35] Chen CW, Huang CH, Dai XK, Huang HC, Chen Y. Motion and control simulation of a dished autonomous underwater helicopter. In: Proceedings of OCEANS 2017-Anchorage; 2017 Sep 18–21; Anchorage, AK, USA. IEEE; 2017. p. 1–6.

[36] Wang Z, Liu X, Huang H, Chen Y. Development of an autonomous underwater helicopter with high maneuverability. Appl Sci 2019;9(19):4072.

[37] Ji D, Chen CW, Chen Y. Autonomous underwater helicopters AUV with disc-shaped design for deepwater agility. Sea Tech 2018;59(8):25–7.

[38] Liu X, Wang Z, Guo Y, Wu Y, Wu G, Xu J, et al. The design of control system based on autonomous underwater helicopter. In: Proceedings of OCEANS 2018 MTS/IEEE Charleston; 2018 Oct 22–25; Charleston, SC, USA. IEEE; 2018. p. 1–4.

[39] Chen CW, Wang T, Feng Z, Lu Y, Huang H, Ji D, et al. Simulation research on water-entry impact force of an autonomous underwater helicopter. J Mar Sci Tech 2020;25(4):1166–81.

[40] Paull L, Saeedi S, Seto M, Li H. AUV navigation and localization: a review. IEEE J Oceanic Eng 2014;39(1):131–49.

[41] Wang Y, Huang SH, Wang Z, Hu R, Feng M, Du P, et al. Design and experimental results of passive iUSBL for small AUV navigation. Ocean Eng 2022;248:110812.

[42] Wang Y, Hu R, Huang SH, Wang Z, Du P, Yang W, et al. Passive inverted ultra-short baseline positioning for a disc-shaped autonomous underwater vehicle: design and field experiments. IEEE Rob Autom Lett 2022;7(3):6942–9.

[43] Rypkema NR, Schmidt H. Passive inverted ultra-short baseline (piUSBL) localization: an experimental evaluation of accuracy. In: Proceedings of 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS); 2019 Nov 3–8; Macao, China. IEEE; 2019. p. 7197–204.