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Review Article
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# Underwater glider fleet control and application: State of the art and future prospect

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**Abstract:** Underwater gliders (UGs), as efficient ocean observation platforms with long-endurance, are extensively utilized in ocean exploration. They have evolved into a crucial research frontier of cooperative observation network systems. However, the systematic review currently remains at the individual glider level, lacking a comprehensive fleet network to integrate these advancements. This study initially reviews recent literature on UG applications in the ocean and assesses the current research trajectory of UG fleet networks. The utilization of fleets is categorized into two main areas: ocean phenomena observation and targets detection. UG technologies emerged into coordination control, task allocation, path planning, and fleet communication are thoroughly evaluated. Subsequently, the shore-based control system is delineated, and the potential of networked formations is forecasted. The persistent challenges in this domain are pinpointed, offering guidance for future research avenues in UG fleet.

**Keywords:** underwater glider fleet; fleet technology; cooperative control; ocean observation; ocean detection

## 1 Introduction

As the dominant feature of our blue planet covering 71% of Earth's surface, the ocean remains one of humanity's least explored frontiers with merely 5% of its depths charted. This vast aquatic realm maintains multidimensional significance through its physical-chemical-biological interactions that sustain global ecosystems and socioeconomic development. Recent decades have witnessed intensified global strategic priorities on marine resources, driving exponential growth in demand for advanced deep-sea exploration and precision target detection technologies.

UGs emerge as transformative solutions, demonstrating enhanced operational endurance (3000+ km range) and expanded detection coverage compared to conventional underwater equipment. Having achieved technological maturity in autonomous navigation and multi-sensor integration, modern UG systems enable persistent monitoring capabilities across four-dimensional marine environments. Their deployment facilitates unprecedented large-scale sustained observation missions lasting 6-12 months, revolutionizing methodologies in marine environmental research through high-resolution data acquisition of dynamic seabed-topogra0070hy interactions.

Since the concept of the UG was proposed by Henry Stommel [1], it has been developed for more than 30 years in foreign countries, the United States in the 1990s. Slocum)[2], Seaglider [3], Spray [4] and SeaExplorer glider [5] have been successfully developed. Tianjin University started the research and development of the first-generation glider in 2002. The thermal glider, Petrel, was successfully developed and conducted the sea trial in 2005. In the same year, Shenyang Institute of Automation developed the Sea-wing glider, revealing that China's UG technology is breaking the foreign technical blockade [6-8], Since then, many domestic agencies have gradually made the research conducted in-depth research on UG technology. National ocean technology center[9], China ship scientific research center[10], China Shipbuilding Industry Corporation[11], Zhejiang university[12], Dalian Maritime university[13], Ocean university of China[14], Institute of Acoustics, Chinese Academy of Sciences[15], Shanghai Jiaotong University[16]. Huazhong University of Science and Technology provides a water-jet propulsion deep-sea glider to adapt to the harsh marine environment [17], Wave gliders with webbed wings proposed by Jiangsu University of Science and Technology overcomes the problems of low energy conversion efficiency and poor maneuverability [18].

At present, with the continuous development of UG technology, some researchers have put forward the application prospect of multi-UGs observation in the future [19]. With the gradual complexity of the application environment of UGs, a single UG cannot meet the needs of monitoring and detection tasks. The UG fleet is of great marine significance for marine environment observation, marine resource development, and marine environment index monitoring. Therefore, the networking technology of UGs has become the focus of research in recent years. The cooperative observation technology of UG fleet is a kind of UG fleet network, which uses multiple UGs to cooperate so as to realize specified mission. UGs play different roles in the fleet, such as navigators and data collectors, and use certain communication technologies to cooperate. The reception and transmission of information can improve the accuracy and efficiency of observation, greatly enhance the scope of observation, realize three-dimensional full-enclosed observation, and provide high-resolution monitoring data, which is suitable for the observation of mesoscale and sub-mesoscale eddies.

In the 21$^{st}$ century, most of the other countries began to study the multi-UGs coordination technology, preparing to establish the prototype of the UG observation network. In 2003, the AOSN network constructed by the America indicated that the technology research and development of UGs would be transformed from a single UG to multi-UGs [20]. Besides, the IOOS ocean observation network [21], EGO system established in Europe [22], Woods Hole Institute of Oceanography [2], Scripps Institute of the United States [4], Australian IMOS [23], South African CSIR-NRE [24-25] , U.S. Navy Research Institute [26], Canada's Monterey Institute of Oceanography [27-28] and the University of Washington Laboratory [29] have also gradually followed up the construction of the UG ocean network.

The contributions of this study include:1) A comprehensive review and analysis of the development status and historical process of the transformation of UGs from single-vehicle to fleet at home and abroad; 2) The application of UG fleet in the ocean phenomena observation is detailed described; 3) Extended detection of UG fleet in the field of underwater acoustics is reviewed; 4) The coordinated control technology of UG fleet is deeply discussed, and its development trend is revealed, which lays a theoretical foundation for future fleet technology; 5) The research status of shore-based control platforms for UG fleet is deeply analyzed and summarized; 6) The future research directions and possible challenges in the field of UG fleet coordination control technology are proposed, which provides useful suggestions for further study. Figure 1 shows the overview of research status and development trend of UG fleet.

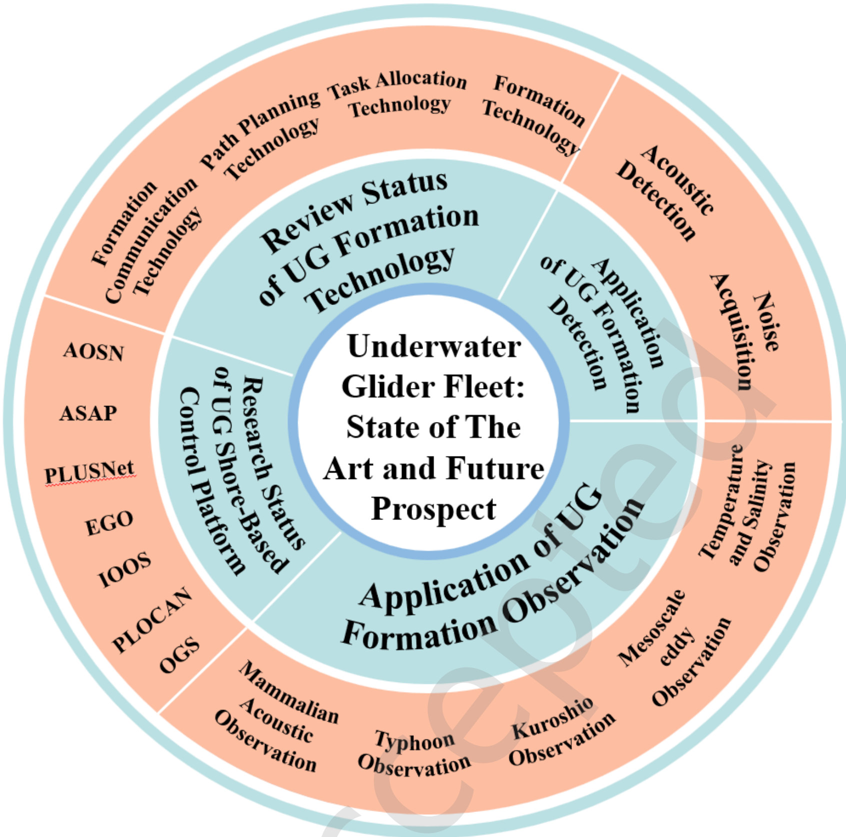


**Figure 1** Overview of research status and development trend of UG networking

This detailed part of the paper is arranged as follows. Section II mainly introduces the observation of UG fleet in mammals, typhoon, Kuroshio, mesoscale eddy, temperature, and salinity. Section III describes the detection of UG fleet in acoustics and noise. In section IV, the UG fleet technology, task allocation technology, path planning technology, and fleet communication technology are summarized. Section V introduces the shore-based control platform of the UG. Section VI looks at the future development of UG fleet technology. This paper provides an important reference and guidance for related research through a comprehensive review of the coordinated control technology of UG fleet. Meanwhile, it also points out the direction and challenges of future research and contributes to the development of this field. The detailed structure is shown in Figure 2 and the knowledge graph diagram of UG is shown in Figure 3.

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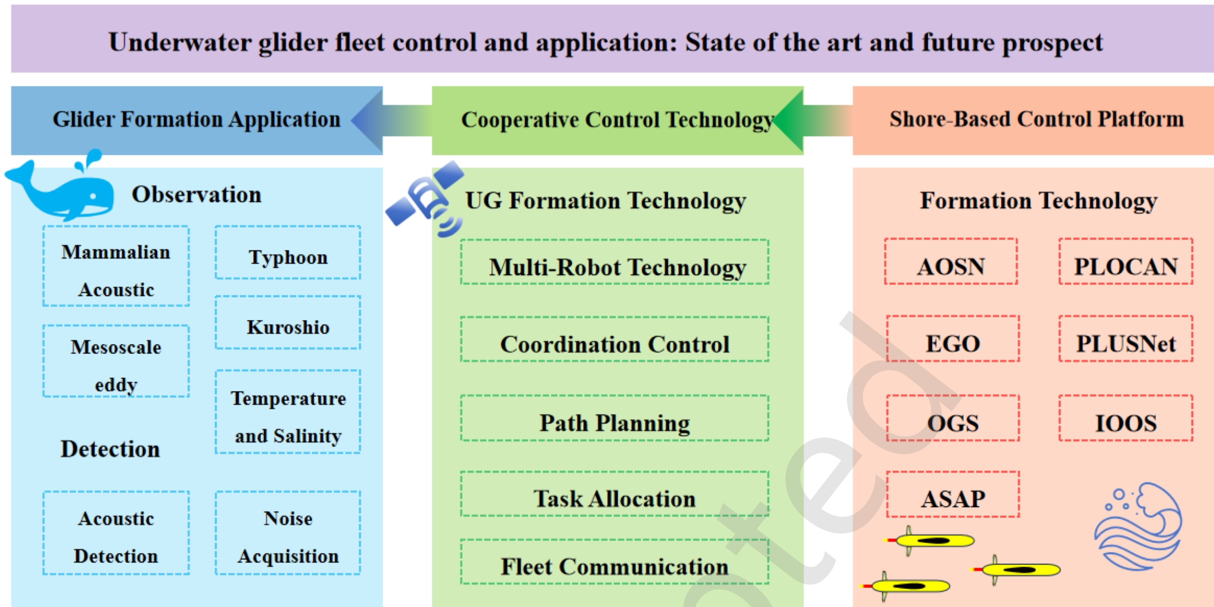


**Figure 2** Research status and development trend structure of UG networking

This study employs knowledge graph visualization to analyze approximately 2,000 Web of Science entries on UGs, elucidating the research domain's intellectual architecture. Node size reflects keyword frequency within the literature corpus, with prominent nodes denoting core concepts including "observation," "motion," and "current." Edge thickness encodes inter-keyword associations; whereby robust connections signify pronounced semantic coupling.

Color-coded clusters demarcate specialized research trajectories: blue clusters predominantly address design optimization; green clusters emphasize dynamics and control strategies; yellow clusters examine hydrodynamics and performance metrics; red clusters investigate ocean observation and detection applications; orange and purple clusters prioritize navigation and path planning methodologies.

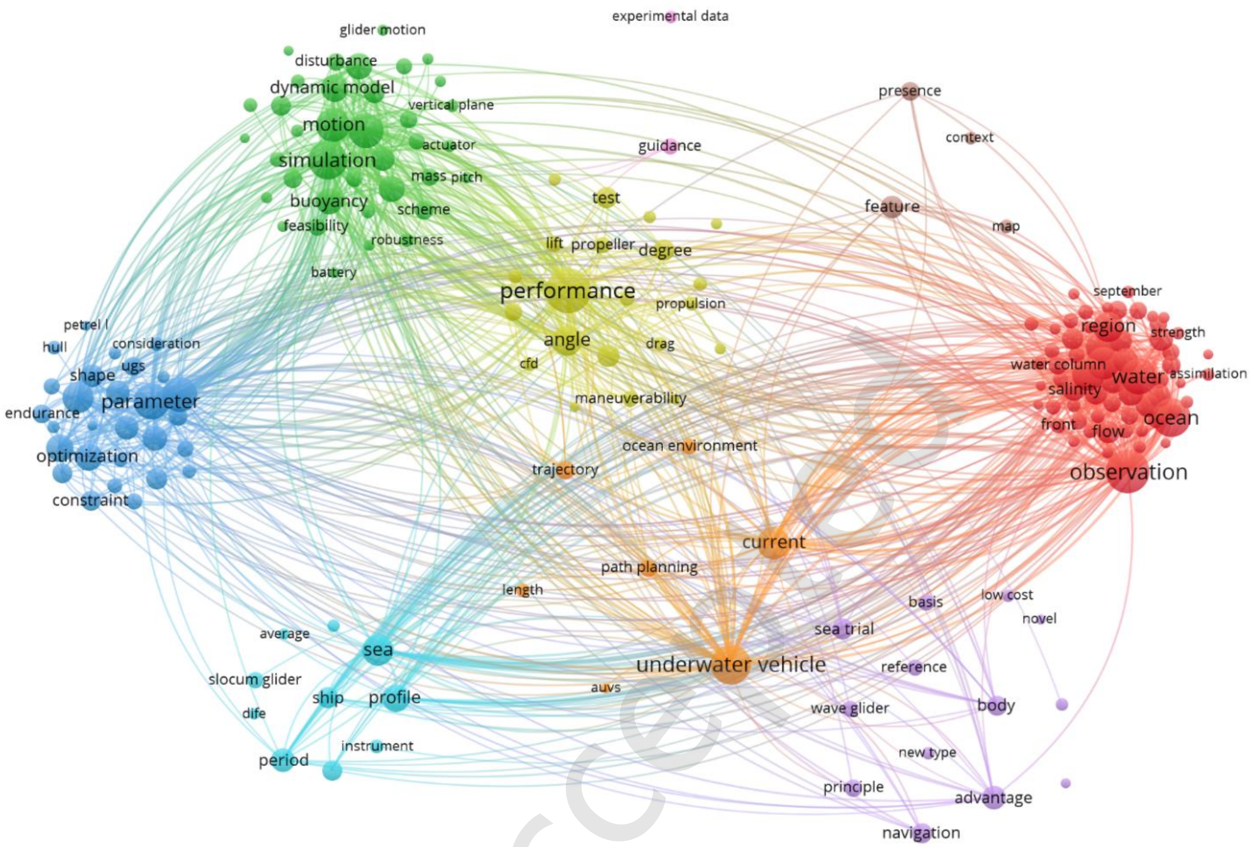


**Figure 3** Knowledge map of UG network

## 2 Glider Fleet Observation Application

This section examines the deployment of UGs across diverse oceanic monitoring domains including marine mammal tracking, typhoon analysis, mesoscale eddy characterization, Kuroshio current studies, and thermohaline structure mapping. Equipped with specialized sensors and imaging systems, UG fleet enable comprehensive monitoring of marine mammal distributions, behavioral patterns, and habitat dynamics while concurrently delivering critical data infrastructure for typhoon trajectory prediction, intensity profiling, and structural diagnostics to enhance disaster preparedness. Mesoscale eddy observation is methodologically streamlined through UG deployments, with captured hydrographic data enabling precise quantification of eddy kinematics and energy transformations critical for understanding oceanic circulation mechanics. The Kuroshio Current's spatiotemporal variability, hydrodynamic properties, and ecological-climatic interactions are subjected to rigorous analysis through coordinated UG sampling campaigns. By acquiring expansive datasets on seawater temperature and salinity gradients, UGs elucidate structural evolution in marine thermohaline stratification, significantly advancing predictive oceanographic modeling frameworks. These autonomous systems demonstrate remarkable versatility in both established and emerging observation paradigms, with particular engineering significance in pioneering unexplored marine territories to expand humanity's operational footprint across Earth's final frontier.

### 2.1 Mammalian Acoustic Observation with Glider Fleet

Mammalian acoustic observation is one of the important means to study marine ecosystems. By collecting and analyzing the call data of marine mammals, we can understand their distribution, population size, reproduction status, and other information. UGs can be equipped with different types of acoustic equipment, combined with UG fleet, through the cooperative operation of multiple gliders, to achieve a larger area of the sea and more types of mammals to observe. Secondly, the fleet of UGs provides continuous observation and high-resolution observation data, which can achieve long-term acoustic observation, high-precision positioning, and monitoring. Since 1998, the U.S. Navy has established a typical underwater acoustic sensor network to promote the combat capability of the Navy. The fixed nodes, mobile nodes, and gateway nodes are connected to a network through the underwater acoustic communication link, which is called SeaWeb. The SeaWeb underwater acoustic communication network test marks that the U.S. military began to carry the acoustic load on the unmanned UG Slocum platform, real-time underwater target, and underwater multi-node information interaction test. To achieve the purpose of observation in the field of mammals, Moore et al. first tried to use acoustic UGs to detect whale calls in 2007 and recorded a large amount of acoustic data. The potential of acoustic UGs in the observation of marine mammal species was confirmed. This breakthrough experiment has opened up a new path for the further development of the ocean observation system [30]. However, Hildebrand et al. furthered this basis, using UGs for observation in 2009, and eliminating self-noise pollution through multi-unit hydrophones. This method not only improves the accuracy of acoustic data but also ensures the orderly progress of monitoring tasks. Their research provides an effective method for long-term monitoring of the presence of mammals in the Southern California coastal area [31]. In 2014, funded by the Whale Habitat and Listening Experiment project of the Marine Environmental Observation Prediction and Response Network Centre (MEOPAR), 11 deployments of gliders equipped with passive hydrophones carried out a two-year cluster networking deployment mission, in which UGs were used to perform whale sound feature recording and data analysis tasks in the mission area. Subsequently, Davis et al. used the UG of the passive acoustic hydrophone system to collect and monitor the expected acoustic data of marine mammals. This method has the advantages of low noise and high acoustic data quality, making the UG important in environmental observation and target detection [32]. In 2017, Wall et al. used the distribution of grouper as the preliminary research object, further expanded the application range of passive acoustics combined with UG technology, and verified the potential utility of passive acoustic methods through sea trial experiments, laying a foundation for the observation and distribution of large-scale fish and marine mammals [33]. In the same year, Uffelen et al. monitored the sound characteristics of marine mammals by UGs combined with acoustic digital detectors, which further confirmed the feasibility of the system in the acoustic observation of mammals and provided a powerful tool for the protection and monitoring of marine ecosystems [34]. In September 2018, two "Petrel 1000" acoustic gliders developed by the Shenyang Institute of Automation Chinese Academy of Sciences completed a joint observation and communication test in the South China Sea for more than one month. 2 gliders continuously observe the marine environmental parameters and sound field information in the test area. At the same time, the observation data of the time-sensitive submersible buoy are obtained through underwater acoustic communication, and the data are sent back to the shore-based monitoring center through satellite communication. The test expands the detection function of the Sea-wing glider and verifies a new mode of mobile-fixed joint observation operation, which provides a new solution to the problem of real-time observation data of the submersible buoy [35]. With the continuous innovation of underwater acoustic equipment, the establishment of an UG network can realize large-scale and high-efficiency marine mammal observation, continuously optimize the real-time transmission capacity of communication data, and monitor mammal data in real-time according to environmental changes and observation needs. It also provides a scientific basis for the use of marine resources in other disciplines and provides strong support for the protection and sustainable development of marine ecosystems.

### 2.2 Typhoon Observation with Glider Fleet

The typhoon that can be observed by the UG is about tens to hundreds of kilometers in diameter. The central wind speed is about tens of meters, and the intensity is relatively weak. It is usually between 8 and 11 levels, and the impact range and destructive power are small. It may not cause large-scale disasters, but it will still have a certain impact on local areas. The duration of small typhoons is short, generally in a few days to dozens of days, and the high endurance monitoring of UGs just fits the small typhoon cycle. Therefore, the UG fleet can observe the development process, path, and intensity changes of small typhoons. In addition, the UG fleet also has the characteristics of flexibility and adaptability. They can be adjusted and optimized in real-time according to the location and intensity of typhoons to obtain the most representative observation data. Through reasonable fleet design and scheduling algorithm, it can realize multi-angle and all-round observation of typhoons, and improve the spatial and temporal resolution and accuracy of observation. In 2013, Miles quantitatively analyzed the spatial variability of sediment resuspension and transport in heavy precipitation during the typhoon event in November 2009 by using the data of two UGs and radar buoys, combined with the cross-sectional wind data of the glider, which is helpful to further explore the influence of typhoon on sediment transport [36]. Domingues et al. continued and deepened this research direction in 2015. They carried out targeted continuous observation of typhoons in the upper ocean. Through the observation of UGs, they improved people's knowledge of how the ocean responds to TC and provided new perspectives and tools for typhoon intensification research and prediction [37]. In 2019, Vargas et al. further explored the application of glider data in typhoon research. They qualitatively combined the glider to detect the typhoon data prediction system, and by analyzing the temperature data of the 2 gliders, they found that the glider data assimilation can affect the vertical stratification before the typhoon storm to a certain extent [21]. This finding provides new possibilities and research directions for typhoon prediction. In the same year, Hsu et al. conducted an in-depth study of typhoons in the Kuroshio region of Taiwan using an UG. They observed changes in characteristic indicators during fourteen typhoons, and combined with observation data, summarized the observation results of typhoon-induced subsurface warming and cooling in the Kuroshio region of Taiwan. This study is of great significance for understanding the characteristics of typhoons and their impact on the marine environment [38]. In 2023, Sun et al. pushed the application of UGs to a new height. They used UG networking to study typhoon observation and obtained the best typhoon observation scheme of UG fleet through the optimized genetic algorithm. This new technology and method can more accurately observe and establish the three-dimensional structure of the ocean induced by typhoons, which provides an unprecedented possibility for typhoon research and prediction [39]. In 2024, Hopson et al. utilized a glider from Rutgers University to collect samples of temperature, salinity, current velocity, and dissolved oxygen concentration during Hurricane Beryl. The data, with an error margin within 17m, offered valuable support for model development and predictive analysis [40].

### 2.3 Strong Current Observation with Glider Fleet

The Kuroshio is the strongest warm current in the western part of the North Pacific, and it is the second-largest warm current in the world. It only lives after the Gulf of Mexico's warm current and turns northward through the eastern coast of the Philippine Islands. It originated in the Philippines islands of Luzon Island east of the sea area, the main channel along the east coast of Chinese Taiwan island. The sea area is large and the traditional underwater vehicle cannot collect complete data on the Kuroshio current. UG fleet has the characteristics of low energy consumption, strong endurance, and high measurement accuracy, and can collect high-resolution data such as Kuroshio temperature and salinity in real-time. As early as 2010, Send et al. proposed a combined hybrid observation method for observing small-scale, strong currents, rich vortices, and other ocean phenomena, to better meet the technical requirements of an UG observation system [41]. In the following year, Todd et al. analyzed the structure and variability of the polar ocean current by using the multi-UG combined with the California Current System (CSS) in the upper ocean, which is of cross-stage significance for the observation of ocean phenomena [42].

Based on the data of two UGs, Miles et al. successfully verified the spatial variability of sediment resuspension and transport in heavy precipitation affected by strong ocean currents in 2009 through radar buoy Argo data in 2013 [36], It lays a theoretical foundation for the data observation of multiple UGs under the action of ocean currents. Three years later, Shu et al., based on the application prospect of the UG in ocean phenomena, combined with the high-resolution observation data of the glider, analyzed the anticyclonic eddy water mass and concluded that the eddy characteristics were similar to those of the Kuroshio, which verified the influence of the Kuroshio on the fleet of the eddy [43]. In 2019, Hsu et al. used UGs to study the changes in characteristic indexes during 14 typhoons in the Kuroshio region of Taiwan. Combined with the parameter data of each index of ocean current, they analyzed the influence of ocean phenomena in the Kuroshio and its extension area on the observation of seawater characteristics [38]. In 2024, Tang et al. introduced an innovative robotic fish featuring a fully flexible compliant shell, advancing prior biomimetic designs. Achieving speeds up to 0.69 m/s, this design excels in demanding underwater environments, such as high-velocity ocean currents, while offering critical insights into enhancing robotic fish performance and maneuverability [44].

### 2.4 Mesoscale Eddy Observation with Glider Fleet

Mesoscale eddies generally refer to ocean eddies with a life cycle of tens of days to hundreds of days and a diameter of tens or even hundreds of kilometers. About tens of kilometers of eddies are generally generated by the decrease of horizontal density gradient, which is also called baroclinic instability. Large-scale eddies are generated by the instability of strong horizontal shear motion. According to the direction of cyclones, they are divided into cyclonic eddies and anticyclonic eddies. Cyclonic eddies bring the cold water in the lower layer to the warmer water in the upper layer, so that the water temperature inside the eddies is lower than that of the surrounding seawater, while anticyclonic eddies carry the warm water in the upper layer into the cold water in the lower layer, and the water temperature inside the eddies is higher than that of the surrounding water. Therefore, it is also called cold eddy and warm eddy.

In 2001, the research of UGs in China had just taken shape. Webb et al. used the UG fleet network to observe and collect the characteristic index data of eddy current and ocean front. Based on considering the advantages and disadvantages of UGs, the importance of UGs to ocean observation was analyzed, which provided a theoretical basis for the subsequent study of mesoscale eddies in UG networking (Webb et al., 2001) [2]. With the deepening of research, Send et al. in 2010 based on the current technical methods cannot fully meet the requirements of the observation system, to solve the global ocean observation capture small scale, strong current, rich eddy, and other complex environment observation problems, put forward a kind of UG merge hybrid method [40]. In the following year, Rudnick et al. introduced the sampling operation process of spray and season. By comparing the adjacent vertical sections, they provided a preliminary evaluation of the influence of internal solitary waves and deeply studied the characteristics of spray at short wavelength and constant depth [45]. In 2013, Pietri et al used an autonomous UG to observe the upwelling system in southern Peru. Through high-resolution, temperature and salinity data, they analyzed the sub-mesoscale filiform structure across the coast, indicating that the sub-mesoscale turbulence stirs the salinity gradient through the mesoscale eddy field, and concluded that the instability of frontal cross-drive may play a role in inducing vertical velocity [46].

Besides, Rudnick measured the vertical velocity of the UG based on a model method and analyzed the pitch motion of the UG. The experiment proved that the slow profile velocity of the UG allowed the observation of high-frequency internal waves [47]. Baltes et al. introduced the glider network's implementation of the Assistance Data Plan, demonstrated the impact of the glider network, and established relevant ocean models for monitoring the reproduction of harmful algae in the ocean, tsunami debris, hurricanes, and oil spills. The strategic significance of UGs in ocean monitoring was emphasized [48]. In 2015, Bosse observed the temperature and salinity structure of the sub-mesoscale eddy through the UG network, analyzed the high-resolution and high-precision temperature and salinity data, and verified that the temperature and salinity structure would diffuse with the mesoscale eddy [49]. Meanwhile, Rudnick used the UG to observe the dynamic complexity and irregular short period of the smaller cyclone eddy current and used the UG observation data to analyze the ocean state estimation and test the model prediction, which verified the value of the UG observation data [50]. In the next year, they used the accessibility of UGs at a horizontal length of one kilometer to observe mesoscale and sub-mesoscale ocean phenomena, such as fronts and vortices, to measure internal waves and turbulent dissipation on a further precise scale, and predicted the future position of UGs in ocean observation [51].

Additionally, Thompson et al. collected the sub-mesoscale time series of buoyancy gradient, potential vorticity, and instability characteristic information of one-year ocean phenomenon by UG, which provided a complete period information for the study of ocean sub-mesoscale, and will be accurate in the future [52]. A detailed structure of an anticyclonic eddy over the northern South China Sea in the spring of 2015 was analyzed by using high-resolution observation data from an UG combined with glider fleet. Water mass analysis shows that the eddy is similar to the Kuroshio, confirming that the eddy originated from the Kuroshio intrusion [43]. In 2018, Zhao established an observation framework suitable for UGs to track and identify mesoscale eddies, analyzed the existing mesoscale eddies tracking technology data and recognition results, and finally verified the tracking and observation of irregular ocean dynamic characteristics by UGs [53]. To keep the UG in a predetermined relative position in the observation task, Zhao et al. proposed an UG fleet control strategy suitable for the observation of oceanic mesoscale eddies. Through the simulation system experiment, the tracking sampling observation task of circular trajectories with different radii in the eddies was completed [54].

Aulicino et al. studied a comprehensive UG observation system for mesoscale and submesoscale characteristic phenomena in the Algerian basin. Through the high-resolution glider observation data, the mesoscale and submesoscale eddies are visually predicted and evaluated, which has important marine significance [55]. Evans et al. used the UG to observe the vertical water velocity in the mid-latitude region of the North Atlantic and estimated the turbulent dissipation rate based on the large eddy method, and compared it with the dissipation rate estimated by mooring, which verified the rationality and effectiveness of the method [56]. Li et al observed the vertical structure of the eddy using the high-resolution data collected by the UG. Through the analysis of the data, the high variability of the anticyclonic eddy in the South China Sea and the causes of the anticyclonic eddy were verified [57]. Zong et al. designed a method for in-situ observation of mesoscale eddy hydrology and kinematics by UGs.

Based on the separation principle of the navigation process and observation process, the temperature and salinity distribution of mesoscale eddy was successfully measured, which laid a technical foundation for UG in the field of mesoscale eddy observation [58]. Based on the functional characteristics of UGs and the characteristics of internal wave motion, Liu et al. proposed a method for in-situ observation of internal waves by UGs in neutral hover and with body. Through sea trial experiments, the three-position kinematic structure model of internal waves was successfully established, which plays an important role in in-depth observation of the data characteristics of internal waves [59-60]. Viglione et al. used two UGs to sample data in the upper and lower reaches of the Drake Strait fault zone and analyzed the differences between the two sides. The mixed layer depth in the lower reaches is twice as deep as that in the upper reaches. The results prove the role of sub-mesoscale instability in generating mixed-layer variance [61].

In 2019, Li et al. collected anticyclonic eddy information from UG deployment combined with high-resolution in-situ glider data to establish a three-dimensional structure of the eddy. By comparing the terrain analysis of the water mass, the ability of the UG network to observe the accurate three-dimensional structure of the mesoscale eddy is verified, which lays a technical foundation for the observation of the ocean eddy phenomenon [62]. In addition, twelve sea-wing gliders were deployed to complete the cooperative networking observation application of China's multi-parameter UGs in the Indian Ocean. The network system performs cluster collaborative observation in the 300n mile×300 n mile observation sea area. The navigation distance is 12,000 km and the scientific observation of 3400 profiles is completed. This task provides theoretical support for revealing the mesoscale eddy of the ocean, the hypoxia of the northern Indian Ocean, and the change in the marine hydrological environment [63].

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The application of UGs in mesoscale eddies, the sea area involved, the number of glider fleet, the field results, etc. in Table 1

**Table 1** Research summary of UG fleet in mesoscale eddy

| Year | Application | Sea Area | UG Number | Reference | Field Results |
|---|---|---|---|---|---|
| 2010 | Strong Current, Small-scale eddy | Two Boundary currents of subtropical ocean at 30°N and 30°S Latitudes | Multiple | [40] | A merging hybrid method is proposed |
| 2011 | Internal Solitary Wave | Northern Hawaii | 2 | [44] | Short-wavelength constant-depth Characteristics |
| 2013 | Vertical Velocity, Pitching Motion | Luzon Strait | 7 | [47] | Allowing high frequency internal waves pass through the slow profile velocity |
| 2013 | Monitoring of Harmful Algal blooms, tsunami debris, hurricanes and oil spills in the ocean | US Coastal Waters | sixty | [48] | Overview of basic information about IOOS system in US coastal waters |
| 2015 | Complexity and Irregular Short Period of Small Cyclone Eddy | Gulf of Mexico Circulation | 2 | [50] | Validation of observational data |
| 2016 | Submesoscale Time Series | Subtropical Northeast Atlantic region | 2 | [52] | Providing a complete time period |
| 2016 | Anticyclonic Eddy | South China Sea | twelve | [43] | The eddy originated from the Kuroshio |
| 2018 | Mesoscale eddy tracking observation | South China Sea | Multiple | [53] | Achieve irregular ocean dynamic feature tracking |

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| | | | | | |
|---|---|---|---|---|---|
| | | | | | observation |
| 2018 | Mesoscale eddy observation | Constant-velocity moving eddy | 4 | [54] | The circular trajectory tracking sampling of the eddy with different radius |
| 2018 | Vertical structure of anticyclonic eddy | South China Sea | twelve | [57] | High variability of anticyclonic eddy separation and its causes |
| 2018 | In-situ observation of mesoscale eddy | Mesoscale eddy | 2 | [58] | The distribution and three-dimensional structure of temperature and salinity were successfully observed. |
| 2018 | Submesoscale instability | Upstream and downstream of the Drake Strait fault zone | 2 | [61] | The influence of mesoscale instability on the variance of mixing layer |
| 2019 | Anticyclonic eddy | Northern South China Sea | twelve | [62] | The effectiveness of the UG network in observing the three-dimensional structure of mesoscale eddies is verified. |

1

### 2.5 Temperature and Salinity Observation

Temperature and salinity observation plays an important role in the prediction of marine phenomena. Temperature and salinity indicators are the basic parameters for studying the basic characteristics of the marine environment, monitoring climate change, and the laws of marine ecosystems. Through the distribution and variation of temperature and salinity, the characteristics of the ocean can be inferred. The UG for temperature and salinity observation can monitor the temperature and salinity of the marine area in real-time by carrying sensors with different parameters of temperature and salinity and can obtain long-term series of temperature and salinity data. In the observation process, the ocean model can be constructed based on the temperature and salinity information obtained by the UG network.

Since 2011, Todd et al., combined with the observation results of the UG of the California Ocean Current System (CCS) in the upper ocean process, obtained the three-dimensional structure and variability of the eddy, transport, and polar ocean current, as well as the influence on the temperature and salinity structure in the EI region [42]. In addition, Mourre et al. conducted two sets of model observations using an UG to explore the uncertainty of ocean temperature in Liguria. Through the sea trial data, it is verified that the optimization of the structure of the UG in the sea area can reduce the uncertainty of temperature to a certain extent [64]. The temperature and salinity detection ability of the UG is not only affected by the performance of the equipment itself but also by the marine environment, such as vortices, ocean currents, cyclones, and other environmental factors. Therefore, the UG needs to combine multiple factors in the detection of temperature and salinity. In 2013, Pietri et al. used the UG to extract high-resolution, temperature and salinity data from the rising basin in southern Peru, further analyzed the influence of temperature and salinity data in sub-mesoscale turbulence, and verified the temperature and salinity structure changes induced by frontal vortices [46]. In 2015, Qiu combined the sea-wing UG observation data and satellite observation data to study the response of the upper ocean cooling to the wind direction change.

Through the quantitative analysis of the heat budget, it is proved that the entrainment caused by the deepening of the mixed layer depth (MLD) has an important contribution to the cooling of the ocean mixed layer (ML) [65]. At the same time, Bosse observed the temperature and salinity center structure of the sub-mesoscale eddy current and revealed the diffusion phenomenon of the sub-mesoscale eddy current waters in the warm/salty intermediate waters through the fleet of UGs [49]. In 2017, Lindstrom et al. studied the sea surface salinity model and variation of the SPURS I and II projects. Using the Lagrangian and Eulerian methods, they coordinated sampling on different platforms and finally captured the salinity process of the upper ocean [66]. Besides, Li et al. studied the high variability of the anticyclonic eddy in the South China Sea and the vertical structure of temperature and salinity in different sections. Combined with the high-resolution data collected by the UG, it is concluded that the anticyclonic eddy may be generated in the Kuroshio [57]. By using in-situ observation fusion of mesoscale eddy hydrology and kinematics, Zong et al. observed the three-dimensional structure and temperature-salt model of mesoscale eddy accurately through the sea trial experiment of the UG, which is helpful for the further study of the UG in mesoscale eddy observation [58].

In addition to the large-scale comprehensive observation network, the U.S. Navy Marine Agency achieved simultaneous command and control of fifty glider tests in 2018, and is ready to deploy one hundred gliders at the same time to seek new ways to achieve automation and improve efficiency. Hsu et al. studied the changes in temperature and salinity characteristics during fourteen typhoons in the Kuroshio region of Taiwan by using an UG. Combined with the real-time changes in seawater temperature and salinity, the observation results of the subsurface temperature increase and cooling caused by typhoons in the Kuroshio region of Taiwan were finally given, which has certain marine engineering significance for the observation of seawater temperature and salinity characteristics [38]. In 2020, scientists from the Marine Science Division of the U.S. Naval Laboratory optimized the position sense of UGs in marine environmental surveys and the comprehensive utilization of glider data to improve the Navy's ability to predict marine conditions. At the same time, the research team conducted experiments off the coast of North Carolina and found that if both the fleet and the data assimilation method were used, the observation results could be improved by 9%-12%. In addition, Chu et al. observed the temperature and salinity data of mesoscale eddies in the northern South China Sea by an UG to analyze the temporal and spatial evolution of cyclonic eddies in the northern South China Sea [67]. In 2023, Brown et al. measured the seawater characteristics of the New Jersey trans-continental shelf transect through a Slocum glider, combined with high-resolution characteristic data, reflecting the temperature and salinity characteristics of cold pool water (CPW) [68]. In 2025, Broadbent deployed six Slocum gliders to analyze a decade's worth of marine ecological data from the Gulf of Mexico, enabling more precise tracking of its dynamic ecosystem [69].

## 3 Glider Fleet Detection Application

This section investigates hydroacoustic detection and ambient noise profiling through acoustic wave propagation dynamics in marine environments. Acoustic sensing systems enable both remote target characterization—capturing spatial coordinates and morphological parameters—and biological activity monitoring through marine organism behavioral analysis and habitat evolution tracking. Noise acquisition protocols emphasize non-target signal discrimination coupled with UG self-noise mitigation protocols through spectral optimization. Ambient acoustic signatures facilitate marine environmental fingerprinting, enabling quantitative assessment of acoustic contamination levels and marine organism ethological studies, including migratory pattern analysis and behavioral ecology insights. Compared to conventional marine acoustic methodologies, UG-deployed systems leverage continuous, real-time data acquisition capabilities to deliver superior precision and operational efficiency in oceanic monitoring missions. The integration of hydroacoustic signature profiling with intelligent noise filtration algorithms significantly enhances marine research capabilities, particularly in long-duration observational campaigns requiring high temporal resolution and signal fidelity.

### 3.1 Acoustic Prospecting

Due to the good propagation of sound waves in the water, the formation of UGs can use sound waves to communicate. By equipping different types of acoustic sensors, long-distance communication can be achieved. Each UG in the fleet is equipped with an acoustic transmitter and receiver, to realize the communication between the gliders and determine its own real-time position and attitude adjustment. The propagation characteristics of sound waves enable the UG to perceive the marine environment and change the path planning of the UG according to the high-precision distance to achieve efficient, comprehensive, and high-endurance detection of the marine environment. The vector hydrophone is the most commonly equipped sensor for UGs. Compared with traditional scalar hydrophones and sound pressure hydrophones, it can receive more abundant and detailed sound field information such as sound waves and sound pressure. Sound source localization and direction inference are performed using the received acoustic information such as sound wave velocity and phase. Acoustic detection can be traced back to 2004 when Ogren et al. proposed a stable control strategy for a response-aware distributed environment, which decouples the cooperative management of grid formation from network mobility, and adjusts its structure according to the perceived environment to optimize gradient climbing [70]. Akyildiz et al. studied several basic key issues of underwater acoustic communication, discussed the different structures of two-dimensional and three-dimensional underwater sensor networks, introduced the characteristics of underwater channels, proposed a cross-layer method integrating multiple communication functions, and looked forward to the challenges and future of developing efficient networks in underwater environments [71]. While briefly introducing the design and performance of the wave glider, Manley et al., proposed the sea trial application of the acoustic detection modulator on the wave glider and verified the effectiveness of acoustic detection in the new UG [72]. In 2012, Chen et al. studied an UG fleet steering algorithm that integrates underwater acoustic communication. By establishing ocean current models under different conditions, it is finally verified that this algorithm can improve the current resistance and sampling range of UGs [73]. Perry et al. introduced the importance of the use of UGs in ocean exploration missions to supplement existing observation stations. Through a one-day test, it was verified that UGs provide cost-effective high-resolution data for observation stations. Finally, the application prospects of the expected tasks of UGs in the future were planned [74]. Besides, Wang et al. introduced the basic principle of vector hydrophone signal processing, compared and analyzed several DOA estimation algorithms based on single vector hydrophone, and developed an acoustic vector detection system that can be equipped with an UG. The system was applied to the lake and sea test on the UG. Finally, the feasibility of the detection performance of the system was analyzed [75]. Yuan et al. briefly described the preliminary research status of UGs, established the underwater acoustic detection system of UGs, and analyzed the development trend of key technologies of UGs from the aspects of marine environmental monitoring and measurement, underwater target early warning detection, and hybrid platform drive. The echelon configuration and combined use of UGs have greatly improved the marine environment detection and underwater target early warning detection capabilities of UGs [76]. Based on the problems existing in the underwater target detection glider acoustic system, Zhang et al., studied the influence of the acoustic scattering of the glider on the direction-finding performance of the vector hydrophone through the shallow sea test of the target detection performance of the underwater target warning glider, and obtained the root mean square error is about 7° [77]. Wang et al. introduced a self-developed "Dolphin-I" acoustic glider and carried out a target detection performance verification test in the South China Sea. The results show that the maximum detection distance of the UG is more than 12.8 km under certain conditions [78]. Based on the application requirements of the underwater slow-moving sonar platform, Sun et al. designed a co-oscillating vector hydrophone and applied the "Dolphin-1" underwater acoustic glider (UAG) and the "G-Argo" underwater acoustic intelligent buoy to carry out target detection experiments. The results lay a technical foundation for the application of the co-oscillating vector hydrophone in the underwater slow-moving sonar platform [79]. Based on the analysis of the marine environment, the detected target, and the technical characteristics of autonomous underwater glider (AUG), Mo et al., 2019 discussed the AUG environmental monitoring/target detection method in the sea and simulated the AUG detection application experimental method, which provided a certain theoretical basis for related experimental research [80]. Mao et al. summarized the application status of UG cluster in marine environment observation and cluster underwater target detection, and emphatically analyzed the key technologies of UG cluster underwater detection capability, indicating the important role of UGs in global ocean observation and detection system [35].

### 3.2 Noise Acquisition

The traditional AUV will be subjected to fluid resistance during the movement, resulting in large mechanical noise, which will affect the accurate collection of underwater detection target data. The UG uses its buoyancy and gravity to adjust and advance the attitude, resulting in relatively less dynamic noise, to collect high-resolution and high-precision data. In 2010, Hildebrand et al. proposed a method that can monitor the existence information of marine mammals in the offshore area of Southern California for a long time. The multi-unit hydrophone is used to eliminate the self-noise pollution caused by acoustic sensors, to ensure the orderly progress of monitoring tasks [31]. In 2017, Uffelen et al. introduced the application of a developing acoustic digital detector (DMON) system for marine mammal target observation in UGs and recorded the sound activities of various cetaceans through offshore experiments in the archipelago to verify the feasibility of the system. Finally, the problem of self-noise misdetection of future UGs was analyzed [34]. Liu et al. proposed a new hybrid-driven UG driven by a traditional AUV and an UG. The step-by-step operation method was used to analyze the noise experiment. It was verified that mechanical noise was the largest part of the self-noise, which provided technical guidance for the improvement of vibration and noise reduction of UGs [15]. In the same year, Liu et al. proposed an UG combined with a deep-water hydrophone and a data acquisition system. Through the relevant pool test and sea trial test, the feasibility of the technical scheme and the stability of the system was verified, which provided technical support for the experimental study of marine environment detection noise [14]. Sun et al. studied the attitude self-sensing acoustic vector sensor based on the UG platform to test and analyze the working condition noise. The experimental results show that the sensor is suitable for the application of an underwater swaying sonar platform, which is of great significance to the application of acoustic vector sensors in UG platforms [81]. In 2018, Wang et al. studied an UAG with target detection capability and designed a low-noise real-time attitude measurement vector hydrophone and underwater acoustic information processing and real-time analysis system. Through the performance anechoic tank test and shallow sea adaptability test, the farthest target detection distance is obtained, and the stability of direction-finding error is guaranteed [82]. Liu et al. used the "Petrel II" AUG to analyze the underwater noise spectrum in the South China Sea and used the step-by-step method to quantitatively analyze the noise data of different depths of the "Petrel II" glider, so as to estimate the cross-depth underwater environmental noise [59-60]. In 2019, Wang et al. developed an UAG with the ability to detect underwater targets. The self-noise of the vector hydrophone and the UG platform was tested and analyzed. The results show that under good hydrological conditions in the deep sea, the UAG has a maximum detection distance of more than 14 km for the test ship target with a speed of 10 kn, which has important guiding significance for guiding the glider noise reduction processing [83]. In the following year, Sun et al. introduced the research progress, system composition, and function of UAGs at home and abroad, and discussed the application of UAGs and key technologies such as vibration and noise reduction, autonomous control, and target autonomous discrimination, which provided a reference for the research and development of UAG system technology [84].

## 4 Research Status of UG Fleet Technology

At present, many researchers are working on the breakthrough of UG fleet technology. The main gliders' projects and field results of UG fleet are shown in Table 2.

**Table 2** Implemented multi-glider coordination projects

| Year | Application | Sea Area | UG Number | Control Architecture | Communication Method | Reference | Field Results |
|---|---|---|---|---|---|---|---|
| 2005 | Ocean Domain Detection | Monterey Bay | 3 | An improved VBAP method | RF Modem, Iridium (RUDICS), ARGOS, Acoustic Modem | [20] | Successful implementation of triangular fleet |
| 2009 | Three-dimensional ocean environment | Simulation of Ocean | Multiple | A robot cluster decentralized architecture and distributed control | Simulation | [85] | Basic group behavior can be achieved |
| 2010 | Adaptive sampling and prediction (ASAP) test | Monterey Bay | 6 | New coordinated motion control technology | RF Modem, Iridium (RUDICS), ARGOS, Acoustic Modem | [28] | Completed adaptive sampling and prediction |
| 2012 | Insufficient sampling in vast sea areas | Simulation of Ocean Current Sea Area | 3 | Fleet steering algorithm based on underwater acoustic communication | Satellite Link | [72] | It is resistant to ocean current and acoustic channel damage and is robust to ocean current and communication obstacles |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 2013 | On-demand sampling planning | Simulation of Ocean Current Sea Area | 3/4/5 | A cluster optimal sampling path planning method based on simulated annealing algorithm | Satellite Link | [86] | Implemented the optimal path planning algorithm |
| 2014 | Avoiding strong current | Simulation of Strong Current Region | 4 | A distributed cooperative path planning method for UGs | Underwater Communication Link or Satellite Communication Link | [87] | The quality of the planned path based on the compressed information is equivalent to the full information |
| 2017 | Complex ocean missions | South China Sea | 3 | A multi-layer index control strategy | Iridium Satellite/Beidou Satellite | [88] | The difference between actual energy consumption and the simulated energy consumption is less than 24% actual energy |
| 2019 | Coordinate UG Fleet | Large 3D Sea Area | 3 | Acoustic glider task management system | Satellite Link | [89] | Lay the foundation for subsequent fleet operations |
| 2019 | Underwater special environment | Simulation of Ocean Current Sea Area | Multiple | A task allocation strategy for AUV cooperative information acquisition | Wireless Underwater Communication | [90] | Comprehensive performance is greatly improved |
| 2020 | Obstacle avoidance | Thermocline Simulation Sea Area | 2 | Complete average path planning obstacle avoidance algorithm (CCPP-OA) of UG in thermocline sea area based | Underwater Sensor Network | [91] | The path planned by this method is shorter and consumes less energy |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | on ACO algorithm) | | | |
| 2020 | Fleet tracking and fleet transformation | Simulation of Ocean Current Sea Area | 4 | An improved AUV particle fleet optimization algorithm | Simulation | [92] | Verifying the simulation validity |
| 2021 | Anomaly detection | The Celtic Sea | 1 | Bidirectional Generative Adversarial Networks (BGAN) | Satellite Link | [93] | The proposed system is robust for Near Real-Time anomaly detection for UGs |
| 2022 | Path planning in ocean current environment | Simulation of Ocean Current Sea Area | 2 | Based on Deep Deterministic Policy Gradient (DDPG) | Subsurface Communication, Satellite Link | [94] | The performance of DDPG is better than DQN |
| 2022 | Uncertain underwater currents | Simulation of Ocean Current Sea Area | Multiple | A distributed robust auction algorithm | Underwater Acoustic Communication | [95] | Improve the ability of multi-AUV task allocation system to cope with the complex underwater environment |
| 2022 | Complex ocean missions | Multi-regional Terrain | 3 | Multi-AUV task allocation method based on multi-objective optimization | Satellite Link | [96] | The allocation of multi-UUV cooperative reconnaissance tasks under multi-objective and multi-constraint conditions |
| 2023 | Underwater target search | IoUT | Multiple | Hunting task allocation framework based on contract network | Underwater Acoustic Communication | [97] | Verifying the balance of its task allocation compared with the normal situation |
| 2023 | Constrained | - | Multiple | Combined with the | Simulation | [98] | The performance of this algorithm |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | multi-objective optimization | | | NSGA-III UUV cluster strike task allocation model | | | is better than that of NSGA-II and AGE multi-objective evolutionary algorithms |
| 2023 | Information communication | South China Sea | 2 | An underwater acoustic communication system based on a non-uniform glider | Underwater Acoustic Communication, Satellite Link | [99] | It lays a foundation for the development of intelligent monitoring of heterogeneous glider coordination networks |
| 2023 | Chain fleet control | Simulation of Ocean Current Sea Area | eleven | Virtual hinge topology | Communication Topology Network | [100] | A good stability and convergence of the fleet |
| 2023 | Leader-follower fleet | Simulation of Ocean Current Sea Area | 3/6 | Radial basis function neural network (RBFNN) and Lyapunov | Simulation | [101] | Verifying the feasibility of the leader-follower approach |
| 2023 | Ocean observation | South China Sea | 6 | Principal component analysis combined with genetic algorithm and back propagation neural network (PCA-GA-BPNN) | Underwater Acoustic Communication, Shore-based Control | [102] | The mean deviation of fleet is about 1.39 km and the time synchronization error is limited to 10 min |
| 2023 | Discrete leader – follower fleet | South China Sea | 3 | Leader-follower and no-leader scenarios under switching communication topology | Underwater Acoustic Communication, Satellite Link | [103] | The theoretical results can be used to deal with the formation control problem for multi-glider systems |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 2023 | Cooperative control | Simulation of Ocean Current Sea Area | 3/5 | Edge computing and digital twin | Underwater Acoustic Communication | [104] | Solving the problem of AUG falling into the local optimal path |
| 2024 | Path planning | Simulation of Uncertain Ocean Current Environment | 4 | A Deep Convolutional Neural Network for uncertain ocean current environment (Duo-CNN) with Deep Reinforcement Learning (DRL) | Simulation | [105] | According to the uncertain ocean current environment and energy consumption of the glider operation, improves the success rate and adaptability of the glider fleet planning |
| 2024 | Comms optimization | The National Maritime Terrestrial Park of the Cabrera archipelago, Balearic Islands | 4 | Acoustic QoS decision | Satellite Link | [106] | Aiding in the development of more effective and efficient coordination strategies for robotic systems in marine environments |
| 2025 | Adaptive neural network control scheme for three-dimensional tracking | Simulation | Multiple | Virtual stabilizing functions and a low complexity error-driven adaptive control strategy | Simulation | [107] | Effectively reducing the computational complexity of the AUV controller |
| 2025 | Area coverage optimized glider | Mediterranean Sea | 4 | Integrating time-varying 3D environmental data | Satellite Link | [108] | Comparing with traditional methods more feasible |

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## 4 UG Fleet Technology

UG fleet technology constitutes a cornerstone for achieving operational efficiency and fleet stability. Coordinated fleet control systems form the fundamental framework for maintaining UG fleet integrity, where precise relative positioning and attitude regulation between gliders becomes paramount due to the inherently complex and unpredictable current environment. Mission architecture design serves as the linchpin of fleet operations, enabling intelligent task allocation and execution sequencing optimization aligned with strategic objectives and operational requirements. Navigational trajectory planning in marine environments demands sophisticated multi-factor analysis incorporating terrain complexity and ocean current dynamics to ensure secure, high-efficiency mission completion. Real-time path optimization through dynamic obstacle avoidance and route recalibration significantly enhances fleet adaptability and operational resilience. Underwater communication networks emerge as critical enablers for collaborative fleet functionality, overcoming aqueous transmission challenges through robust data-link solutions that facilitate seamless data exchange and coordinated decision-making. The synergistic development of these core technologies propels the advancement of UG fleet capabilities, ultimately elevating collective performance metrics and mission execution efficacy across underwater domains. In 2025, Lei *et al.* introduced a real-time dynamic modeling framework that seamlessly integrates environmental factors with robotic systems to enable precise prediction of underwater dynamics, which is foundational for intelligent fleet autonomy [109]. In the same year, Wang *et al.* provided a comprehensive review of the developmental trajectory, performance attributes, and application advancements of long-range underwater gliders, providing a solid basis for the realization of future globally distributed underwater glider networks [110].

### 4.1 Multi-UGs Technology Theory

In recent years, the advancement of UGs has progressed in tandem with the rise of multi-robot formations. Concurrently, the diverse array of technologies deployed in this domain has established a robust technical foundation for UG formation control. In 2023, Cai et al. investigated various swarm coordination modes—including formation control, task allocation, path planning, obstacle avoidance, and collective control—and discussed the impact of artificial intelligence methods such as meta heuristic algorithms and deep learning on underwater robot swarms [110]. Ko analyzed underwater swarm behavior through the lens of hydrodynamic synergy, reviewing related fields such as biomimetic robotics and interdisciplinary fluid mechanics [112]. Yao et al. (2023) introduced an image-based visual servoing control system for leader-follower heterogeneous multi-agent underwater robots, validating its stability and feasibility via pond experiments [113]. Hou et al. concentrated on formation control for small spherical underwater robots, effectively reducing complex formation tasks to individual robot path-tracking problems. Experimental trials with two miniature spherical robots confirmed the approach's practicality [114]. Also in 2023, Li et al. performed comprehensive tests—encompassing path following and static/dynamic obstacle avoidance—to mitigate disturbances from oceanic factors, including obstacles and currents, on biomimetic spherical underwater robots. Real-ocean experiments affirmed the designed control scheme's feasibility, robustness, and effectiveness, offering theoretical guidance for swarm path following and multi-obstacle avoidance [115]. Xiong et al. conceived swarm-game and task-allocation experiments for underwater robot fleet, wherein the swarm continuously learned and refined its strategies, establishing a foundation for more efficient future clusters [116]. Song et al. engineered a biomimetic underwater robot capable of swimming, seabed walking, and obstacle avoidance for marine structural inspection. Water tank tests confirmed the robot's operational stability and feasibility [117]. Yan reviewed recent advances in multi AUV formation control, clarifying and analyzing current challenges posed by complex underwater environments and communication constraints [118]. Mazare et al. tackled heterogeneous AUV formation control by establishing an adaptive sliding mode control strategy, whose effectiveness was verified through simulations and comparisons [119]. Wang et al. proposed an event triggered model predictive control method for multi AUV formation in complex three-dimensional underwater environments, demonstrating its superiority and effectiveness over traditional algorithms [120]. Hadi introduced a novel deep reinforcement learning approach for leader-follower AUV fleet motion planning, validating its feasibility under simulated ocean currents [121]. Wen et al. resolved the dynamic event triggered consensus problem for multiple AUVs， which utilizes an adaptive control method [122]. Kim designed a leader follower cooperative formation strategy for AUVs in unknown 3D environments; MATLAB simulations demonstrated the feasibility of obstacle avoidance under this strategy [123]. Fay et al. utilized shark tracking data to develop an ideal multi AUV formation arrangement and established a dynamic algorithmic model for precise localization and tracking of marine organisms [124]. In 2024, Wu et al. reviewed current swarm control methods for multi robot systems, discussed relevant swarm technologies, and noting that multi robot collaboration, which is becoming an emerging trend [125]. Liu et al. highlighted the important role of AUVs in underwater pipeline maintenance and explored the feasibility of multi robot collaborative path planning, providing theoretical support for future underwater robotics development [126]. Vojnar proposed a trust management framework for multi robot systems aimed at addressing inherent trust vulnerabilities [127].Sun et al. tackled dynamic task allocation for multiple AUVs by employing a game theoretic model based on a multi objective evaluation framework, integrating the AHP and PSO. Simulation analysis confirmed that this model enables real time decision making and task allocation in complex, high dimensional dynamic games [128]. Fan utilized a coil array system to simultaneously control multiple magnetic microrobots. This technology, combined with a multi target tracking algorithm, enables cooperative control of several microrobots and offers guidance for swarm applications in marine environments [129]. Rahaman investigated a virtual structure approach to formation control for robot navigation. Cooperative experiments with four robots showed that this improved A* algorithm yields superior path trajectories [130]. Qu et al. from Tsinghua University provided a multi aspect review of current biomimetic research on underwater soft robots, analyzing outstanding challenges in oceanic currents and complex mission requirements [131]. Ali et al. (2024) evaluated swarm phenomena in multi robot systems, discussing deployment challenges across various domains and offering theoretical insights for multi robot systems [132]. Nguyen et al. presented a comprehensive survey of swarm intelligence, emphasizing the feasibility of bio inspired multi robot systems modeled on natural swarms (e.g., ants, bees, birds, fish) and their collective behavior in solving complex problems [133]. In 2025, Wang et al. outlined the state of multi robot swarms in complex and harsh environments, detailing technologies such as task allocation, path planning, and information transfer methods under local communication constraints [134]. Nazarzehi et al. introduced an innovative approach for underwater target detection and recognition using a deep learning framework and multi AUV swarm, with a YOLOv6 module, the average precision performance was significantly improved by 8% [135]. Kvasic developed a sonar simulator to enable divers to interact with AUVs and issue navigation commands underwater. Gesture based communication represents a promising human robot interaction method, advancing sonar technology and underwater perception innovation, laying a foundation for future diversified robot interaction [136]. Wang et al. proposed a distributed predictive control model based method for cooperative target search by multiple biomimetic fish, which dynamically adjusts paths according to swarm positions in real time to avoid repeated coverage, significantly enhancing system flexibility, scalability, and collaboration efficiency [137]. He designed an underwater exploration mechanism combining an Active Elastic Sheet (AES) swarm model with a semi-autonomous leader-follower model, and developed "bubble" microrobots suitable for swarm based inspection of underwater storage facilities [138]. Ramesh et al. summarized bio-inspired coordination mechanisms in current underwater robot swarm technologies, discussing swarm related algorithms, including the artificial fish swarm algorithm, whale optimization algorithm, coral reef optimization algorithm, and marine predator algorithm, highlighting their roles in formation control, task allocation, and environmental interaction [139]. Ni et al. presented a leader-follower strategy applicable to underwater swarms and realized three-dimensional formation with different shapes on a simulation platform, establishing a basis for future robotic swarm operations in underwater environments

[140]. Tejada et al. explored recent progress in multi robot systems and soft robotics, emphasizing advances in mobility and coordination, and offered insights for developing cooperative multi robot systems [141]. Hua et al. addressed the finite time dynamic regulation problem for multiple robots by proposing a multi robot formation strategy that incorporates a zeroing neural network framework to achieve precise formation control [142]. Lin introduced a hybrid algorithm combining an adaptive robot particle swarm optimizer with a grey wolf optimizer. Simulation experiments with dynamic targets in unknown environments showed that this optimized algorithm outperforms traditional path planning methods [143]. In June 2025, Mataix et al. introduced the Alba series hybrid underwater glider, designed to enhance overall responsiveness, flexibility, and adaptability, guiding the future development of multi modal underwater propulsion systems [144].

### 4.2 UG Fleet Coordination Control Technology

Due to the late start of UGs in China, the fleet technology of underwater robots is relatively mature compared with UGs. 2023 Yan et al. studied and summarized the problems of multi-AUV fleet control, cooperative navigation and positioning, cooperative path planning, task allocation, and hunting, and analyzed the fleet control network architecture, cooperative strategy, and its constraints, which laid a theoretical foundation for the research of AUV in complex marine application scenarios [145]. UGs have gradually developed from single-machine technology to multi-machine technology [2]. After 20 years, Rudnick et al. used the research status of a single UG and combined it with the existing ocean data to boldly assume the development of multi-UG fleet networking in the next decade [19]. In addition, Edward et al. developed a control framework for coordinating the AUV group to the mobile sensor array to perform adaptive sampling of the observation field, so that the coordinated and feasible fleet can perform gradient tracking and feature detection in complex ocean fields. The sea trial of the UG in Monterey Bay during the Autonomous Ocean Sampling Network (AOSN) II project in August 2003 was introduced. In the experiment, the UG was coordinated into a triangular fleet, and the improved VBAP method was used to verify the feasibility of the framework in the application of the UG [20]. The limitations of the UG make it impossible to collect data efficiently in complex mission environments. The fleet of UGs has become the general trend of ocean exploration. In 2008, Paley et al. proposed the UG cooperative control system (GCCS), which can be automatically controlled according to the feedback information of the UG [146]. In 2009, Li et al. proposed a decentralized control strategy for robot swarms. By integrating the neighbor selection process, the control strategy is scalable. Finally, the obstacle avoidance mechanism based on artificial physics is introduced. Using this control strategy, the basic group behavior is demonstrated by simulation in a three-dimensional ocean environment [85]. In 2010, Schofield et al. combined with the research status of UG networking over the years, emphatically analyzed the current application of shore-based systems in UG networking to observe ocean phenomena, which laid a foundation for the diversified development of UG networking ocean exploration [147]. In the same year, Leonard et al. conducted a one-month ASAP experiment in Monterey Bay, California, and established a full-scale AOSN. Combined with the newly developed coordinated motion control technology, 6 gliders used the feedback method for autonomous coordination. Finally, an innovative ocean sampling tool was demonstrated, which provided a theoretical basis for robots in the important field of integrated coordinated motion control and adaptive sampling [28]. In recent years, how to apply fleet performance to UGs in marine phenomena has become an urgent problem to be solved. In 2011, Yang proposed a heterogeneous control system based on an artificial potential energy field method to generate an UG fleet trajectory and used the minimization principle to transform the continuous trajectory into discrete points [148]. Based on the current field data of the regional ocean model, Chang et al. proposed a GENIoS system, which can generate fleet trajectories and sampling points based on the ocean model data [149]. In 2015, Domingues combined the fleet of an UG network to observe the characteristic indexes of typhoons in the upper ocean in a targeted and continuous manner, which provided a theoretical basis for observing ocean phenomena in the upper ocean and contributed to the construction of UG network [37]. At the same time, Bosse observed the diffusion phenomenon of sub-mesoscale eddy waters through the UG networking system, analyzed the high-precision data collected by the glider fleet, and successfully verified the diffusion mechanism of sub-mesoscale eddy waters in the warm/salty intermediate waters [49]. In 2017, Xue et al. proposed a multi-level cooperative control model for UG fleet based on multi-body theory and artificial potential energy field, considering the ocean current field and energy consumption model [150]. Wang et al. proposed the fleet control of UGs by using asynchronous computing and hierarchical control architecture [151]. With the help of acoustic communication, Longhi et al. realized the cooperative fleet of multiple UGs by using a distributed predictive control method and carried out simulation experiments [152]. Tianjin University began to study the network observation of UGs in 2014, mainly focusing on the fleet control of gliders and carrying out fleet tests in the South China Sea. In the same year, Tianjin University used three UGs to carry out fleet tests in the Xisha Sea area to verify the cooperative control ability of UG fleet [153]. In August 2017, eighth gliders and a total of 30 sets of marine equipment were used to carry out a large-scale three-dimensional comprehensive observation network with "petrel" UGs as the core in the central and northern sea areas of the South China Sea. The observation network covers 140,000 square kilometers of sea area from the atmosphere-seawater interface to 4200 meters of water depth. The multi-platform long-term writing observation is carried out on the mesoscale eddy, temperature and salinity, underwater acoustics, ocean current, biochemistry, and other factors in the northern South China Sea. In July 2017, twelve gliders and thirty-two XCTDs were used to observe mesoscale eddies in the northern South China Sea by Shen Zi Institute of Chinese Academy of Sciences, and the inversion of mesoscale eddies was realized [154]. In 2019, Qian et al. introduced the application research of single UGs and fleet networking at home and abroad, as well as the development status of key technologies. Combined with the technological progress that has been achieved, the application of UG fleet is prospected [155]. Mao et al. studied the current application status of UG networking, and prospected and analyzed the key technologies of UG clusters, emphasizing the advantages of UG networking compared with a single machine [35]. Diao et al. analyzed the research status of UGs at home and abroad and focused on the application of UG cluster fleet in ocean exploration. Finally, the overall glider form was prospected [156]. In 2025, Hossain et al. underscored the significance of UGs in current marine applications and, through a comprehensive review, outlined various bio-inspired strategies, including dolphin-inspired and manta ray-inspired approaches, laying the theoretical groundwork for multi-glider formation in complex underwater environments [157]. At the same year, Lu et al. introduced a three-dimensional distributed cooperative guidance-free control model for UGs. Simulations demonstrated its efficacy in coordinating multiple gliders and enhancing disturbance rejection in individual units, tackling a technological gap in UG swarm systems [158].

The existing UG fleet control research has made great progress, but the existing UG fleet cooperative control method still stays at the water surface control level. The local range fleet control adopts the acoustic communication method, which is still constrained by the distance cost.

**4.3 Task Allocation of Glider Fleet**

Task allocation technology refers to the technology that effectively allocates tasks to each glider for the UG cluster to achieve collaborative operation and efficient task execution. The key to this technology is to enable the entire glider system to complete complex tasks through reasonable task sharing. The research on task allocation technology in China started late. In 2017, Xue et al. studied the coordinated control and task allocation of UG fleet by using multi-body mechanics and the artificial potential energy field method. Through simulation experiments, the coordination of fleet motion and the coordinated control of attitude are realized, to successfully allocate the detection and observation requirements of each glider in the environmental three-dimensional observation network [150]. In the following year, Shen et al. introduced the current research status of UG single-machine technology and summarized the key task allocation technology of multi-UG cooperative networking. The development of UG networking technology in the future was prospected [153]. Based on hybrid UG fleet, Xue et al. proposed a multi-layer index control strategy and established a hybrid motion energy consumption model. The feasibility of the method was verified by simulation experiments. It shows that the UG fleet has the advantages of continuous high resolution and adaptability to complex ocean tasks in ocean exploration [88]. At the same time, Zhao et al. proposed an UG fleet control method for stabilizing the position of the glider to observe the mesoscale eddy mission in the ocean, and verified the feasibility and effectiveness of the fleet control method by establishing the relevant UG fleet parameter model and further experiments [54]. In 2019, Barbier et al. studied the application of Acoustic Glider Mission Management System (AGLIMMS) in coordinating the mission of UG fleet and constructed a three-dimensional sea area model through acoustic and other measurement data, and expected to conduct multiple glider sea trials at the end of 2019 [89]. In 2019, Li et al. proposed a multi-AUV collaborative information collection task allocation strategy. The robust Whittle algorithm is used to solve the robust endless gambling machine problem based on reinforcement learning. When the task allocation method strategy corresponds to 1, 2, and 3 targets, the system parameter performance is improved by 5.5%, 12.3%, and 9.6%, respectively [90].

To solve the task allocation problem of heterogeneous multi-AUV, Li et al. proposed a distributed robust auction algorithm, which improves the ability of multi-AUV task allocation systems to cope with complex underwater environments. The strong robustness and applicability of the algorithm are verified by simulation [95]. To solve the problems of premature convergence and low efficiency of single population genetic algorithm, Fan et al. proposed a multi-population co-evolutionary algorithm based on man-machine fusion to ensure the allocation of multi-UUV cooperative reconnaissance tasks under multi-objective and multi-constraint conditions. The simulation results show that the algorithm has strong robustness and high optimization efficiency [96]. In the following year, Zhang et al. proposed a new task allocation method and an improved discrete crow search algorithm (IDCSA) for a multi-unmanned submersible recovery system. The effectiveness and robustness of the two-layer algorithm are verified by simulation [97]. The task allocation of UGs can integrate the task allocation technologies such as UUV and AUV, to optimize the new algorithm. As UGs have attracted more and more attention in typhoon observation, the optimal design of the genetic algorithm is applied to typhoon. UGs with the best typhoon observation task allocation scheme help to more accurately observe and reconstruct the corresponding three-dimensional structure of the ocean induced by typhoon TC [39]. Wu et al. constructed a UUV fleet task allocation model combined with the third-generation non-dominated sorting genetic algorithm (NSGA-III). The simulation results show that the algorithm has good adaptability compared with NSGA-II and the adaptive shape estimation multi-objective evolutionary algorithm [98]. In 2025, Zhang et al. introduced a novel multi objective evolutionary algorithm termed "collaborative swarm differential evolution", which demonstrates superior performance across diverse multi robot task allocation environments [158]. Kim proposed a collaborative region partitioning method for multiple AUVs, designed to optimize inter cluster task allocation and enhance the efficiency of underwater search missions by verifying the feasibility of this approach through simulation of an underwater exploration scenario [160].

### 4.4 Path Planning Technology

At present, the path planning of UGs mainly involves three aspects: traditional algorithm, intelligent optimization algorithm, and multi-algorithm fusion. Compared with single-machine path planning, the path planning of UGs in fleet needs to consider factors such as communication, adaptability, and coordination between fleet. As early as 2013, Gabriele et al. proposed an optimal sampling method for the optimal path planning of UG clusters to meet the acceptable uncertainty of the scientific or business needs of the task. By introducing a new optimality criterion and using a simulated annealing algorithm, the feasibility of this method is finally verified in different situations in the western Mediterranean region by using the ocean current and temperature data obtained from the ocean data model [86]. In 2014, Liu et al. proposed a distributed collaborative path-planning method for UGs to avoid strong ocean currents. Using the vector data description method, they developed a fast-moving algorithm combined with the compression information of the glider. Through simulation experiments, it is shown that the path planning quality based on the compression information of the UG is comparable to that of the fully shared current information [87]. In 2020, Han et al. developed a complete average path planning obstacle avoidance algorithm for UGs in thermocline waters based on the ACO algorithm. Compared with traditional algorithms, this algorithm can achieve complete coverage of the entire sea area, and at the same time ensure the shortest path length and lower energy consumption [91]. Li et al. introduced an improved particle swarm optimization algorithm for fleet tracking and fleet transformation. Through the two-dimensional space simulation of virtual fleet, the tracking error of the traditional particle swarm optimization algorithm is compared, and the effectiveness of the method is verified, to solve the fleet-related problems [90]. In 2022, an UG fleet path planning algorithm based on deep deterministic policy gradient (DDPG) will be applied to the path planning problem in the ocean's current environment. By simulating the actual marine environment, it is concluded that DDPG performance is better than DQN [92]. A new multi-stage heuristic method (MSHM) is used to solve the three-position search path planning problem of the blended-wing UG. The simulation results show that the comprehensive performance of this method is better than other heuristic algorithms [161]. At the same time, Hu et al. used the JADE algorithm to optimize the offline motion planning of the UG. The motion parameters such as yaw angle, diving depth, and pitch angle were analyzed by this algorithm. Compared with the traditional path planning algorithm, it significantly reduces energy consumption and has better adaptability to the complex marine environment [162]. In 2024, Liu et al. designed a maneuverable AUV capable of performing high quality observation and sampling as close as 20 cm above the seabed, that exhibiting strong disturbance resistance, which can plan paths in real time to avoid bottom contact. This work offers valuable insights for the sawtooth shaped motion of nearshore UGs [163]. Yang et al. integrated the Voronoi diagram with the D* algorithm (UG VD*) to propose an enhanced path planning method and process sea trials from the Mariana Trench to the northern South China Sea using the "Petrel-L" glider validated the feasibility of this algorithm [164]. Han et al. introduced a performance prediction method combining CNN MLP model, that establishing a theoretical basis for forecasting UG performance from multidimensional data [165]. Liu et al. noted that sustained observational missions often were hindered by the influence of ocean current, through incorporating a proximal policy optimization algorithm, which enabled UGs to interact with the environment and generate optimal paths for continuous coverage, though further training in unknown settings remains necessary [166]. Jiang utilized a Markov decision process combined with deep reinforcement learning to achieve effective path planning in complex marine environment [167]. Li et al. proposed an AD RRT* algorithm based on alpha shapes and density based spatial clustering of applications with noise, by incorporating feasibility evaluation and a circular region sampling strategy, which offers significant theoretical advantages for local path planning [168]. Tan et al. aimed to improve the efficiency of UG fleet executing multi point detection tasks in complex ocean current, employing a depth averaged current velocity approach and an NSGA-III genetic algorithm, which verified through multiple case studies that the method enhances both motion accuracy and mission efficiency for fleet [169]. At the same time, Li et al. developed a path planning platform system for UGs, utilizing data cases from the South China Sea and the West Pacific, the system achieved a hydrodynamic energy utilization rate of 35.946%, providing a theoretical foundation for multi glider path planning in ocean current [170]. In 2025, Zhou tackled the challenge of uncertain ocean current when UGs tracked long distance linear paths in complex marine environment, he proposed a curriculum enhanced truncated quantile critics algorithm, through simulated current environments demonstrated that this algorithm outperforms standard reinforcement learning methods in tracking accuracy, obstacle avoidance capability, and task success rate [171].

### 4.5 Fleet Communication Technology

The UG fleet communication technology can enable multiple UGs to work together to enhance the observation coverage and improve the observation ability. Each glider collects information from different points to form a three-dimensional observation, so as to achieve comprehensive ocean exploration. Its efficient communication cooperation ensures that the UG performs cooperative motion and task execution in a complex unsteady environment, improves the stability and robustness of the communication system, and can adapt to observation in various environments. In order to solve the problem of insufficient spatial and temporal measurement of down-sampling in the vast ocean, Chen et al. proposed a fleet steering algorithm based on underwater acoustic communication by using multi-UG network coordination and established different ocean current models to evaluate the performance of the proposed algorithm. It is confirmed that the fleet coordination can make up for the current resistance and coverage of the single-machine case to a certain extent [72]. Baltes et al. discussed the glider technology network technology, analyzed the network and other aspects, focused on the construction and impact analysis of the UG network, and carried out the model establishment of the relevant UG network. Finally, the feasibility of the UG was successfully verified in the application of marine monitoring [48]. In 2016, Yu et al. summarized the system composition of deep-sea gliders in power, control, communication, and detection. Taking the Sea-wing UG as an example, the development and current situation of UG technology and applications at home and abroad were introduced. Finally, the development trend of UG technology was analyzed and the application prospect of gliders in future sea area observation networks was prospected [172]. In 2021, Wang et al. proposed a cooperative controller structure and its design method for UGs. The communication network is connected to multiple controller units after an aperiodic communication mechanism, to achieve information interaction between UGs. This method can significantly reduce the communication burden, reduce energy consumption, and meet the actual needs of long-term ocean observation [173]. In 2023, Tian et al. proposed an underwater acoustic communication system based on non-uniform gliders and carried out sea trials in the South China Sea. The research has laid a solid foundation for the intelligent monitoring and communication technology of heterogeneous glider cooperative networks [97].

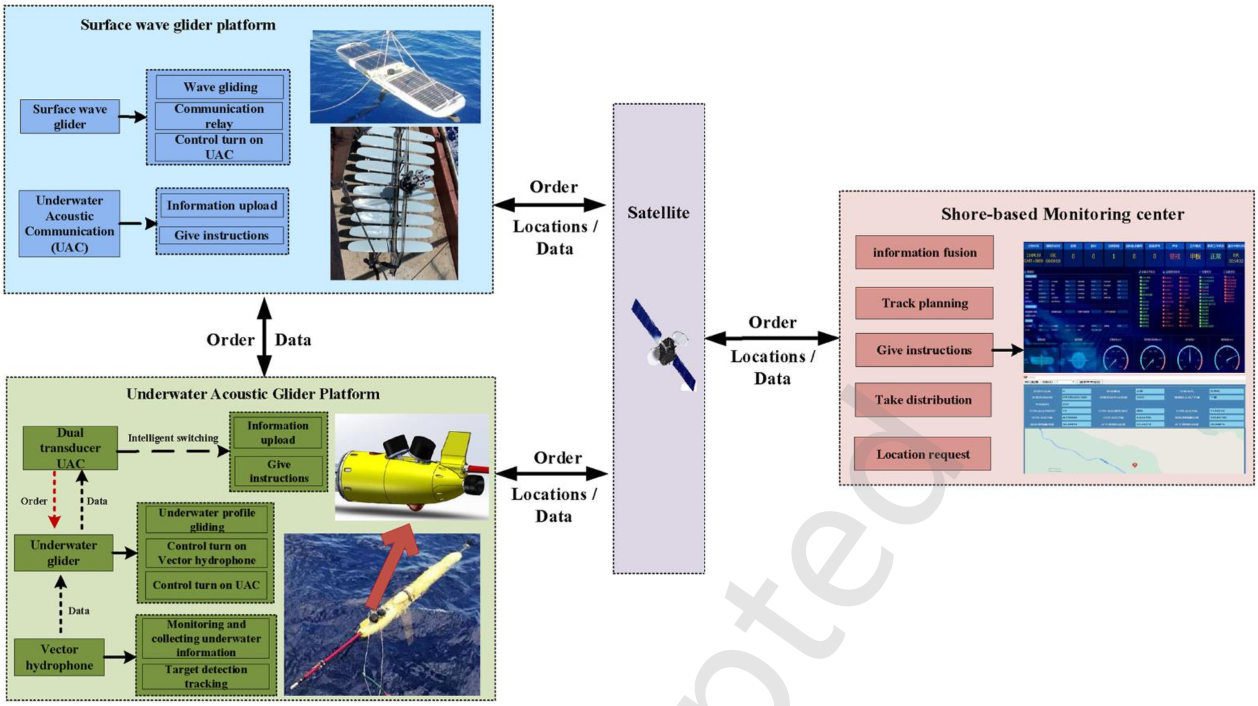


**Figure 4** Architecture of the UG about control and communication (Reproduced with permission from Ref. [99] ©2023, Elsevier Ltd.)

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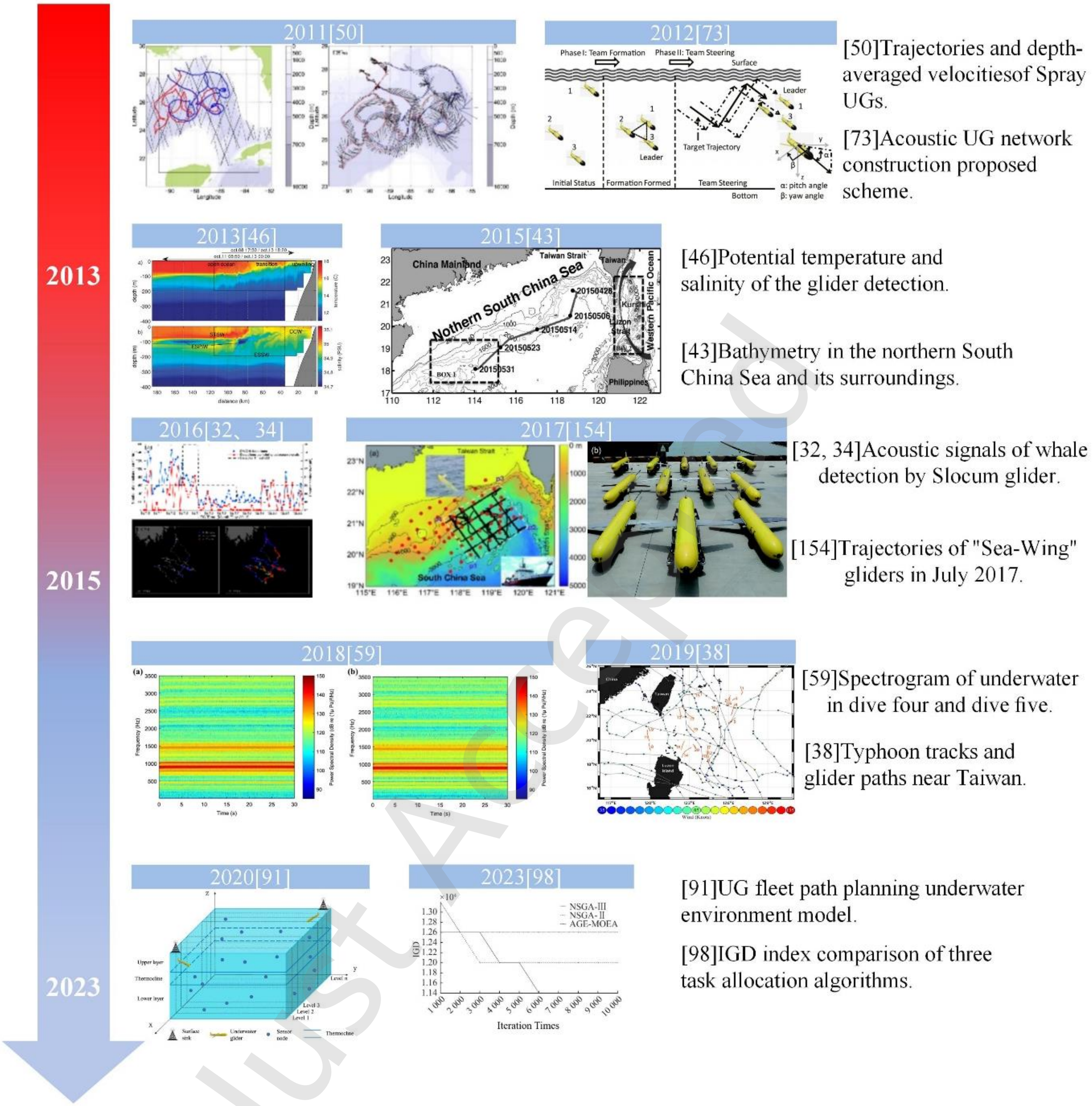


**Figure 5** The development of underwater glider technology applications. The images are reproduced with permission by copyright as follows: Ref. [34] ©2017, IEEE; Ref. [32] ©2016, OCEANS 2016 MTS/IEEE Monterey; Ref. [38] ©2019, The Oceanographic Society of Japan and Springer Japan KK, part of Springer Nature 2018; Ref. [43] ©2016, AEHMS 2016 AEHMS; Ref. [50] ©2015, American Meteorological Society; Ref. [46] ©2013, American Meteorological Society; Ref. [73] ©2012, Elsevier B.V.; Ref. [59] ©2018, Australian Acoustical Society; Ref. [154] ©2017, Science China Press and Springer-Verlag GmbH Germany, part of Springer Nature; Ref. [98] ©2023, China Shipbuilding Industry Corporation; Ref. [91] ©2020, IEEE.

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## 5 Research Status of Shore-based Control Platform (SBCP) for UG Fleet

The shore-based control platform of UGs has become one of the research hotspots. With the joint efforts of many domestic and foreign units and university institutions, the research on the shore-based control platform of UGs has made achievements. The following will introduce the research status of the shore-based control platform of UGs in detail through Table 3.

**Table 3** UG shore-based control platform research status

| Year | Nation | SBCP | Glider Type | Depth | Endurance | Horizontal Speed | Vertical Speed | Payload | Sensors | Typical Test | References |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2003 | USA | AOSN/AOSN-II | Spray, Slocum | 40-1500m | 100+ days | 0.25-0.35m/s | 0.1-0.2m/s | 3-6 kg | Conductivity-Temperature-Depth (CTD), Chlorophyll, Fluorometer | ASAP, COOP, GCCS | [20, 28, 68, 108, 174, 175] |
| 2006 | USA | PLUSNet | Seaglider, Liberdade class | 40-1000m | 6-10 months | 0.25m/s, 0.5-1.5m/s | 0.1-0.3m/s | 3-4.5kg | Electric Field Sensor | Unmanned combat network system | [176-177] |
| 2005-2014 | Britain, France, Germany, Italy, Spain, Norway and | EGO | Slocum, SeaExplorer, Seaglider | 40-1000m | Several months | 0.1-0.35m/s | 0.1-0.2m/s | 3-6 kg | CTD, Passive acoustic monitoring | 300 long-term ocean observation missions | [22] |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | other European countries organization | | | | | | | | | | |
| 2002 | USA | IOOS | Slocum, Seaglider, Spray | 40-1000m | Several months | 0.25-0.35m/s | 0.1-0.2m/s | 3-6kg | CTD, Optical, acoustic, and chemical sensors | PORTS | [21, 22, 48, 178, 179, 180, 181] |
| 2007 | Spain | PLOCAN | Slocum G3, Seaglider, SeaExplorer | 40-1000m | 4-18 months | 0.35m/s | 0.1-0.2m/s | 3-4kg | CTD, Optical, acoustic, and chemical sensors | Real-time Monitoring of UG Tasks | [182, 183, 184, 185] |
| 2005 | Italy | OGS | Slocum G2/G3, | 40-1000m | 3-9 months | 0.25-0.5m/s | 0.1-0.2m/s | 2-7kg | CTD, SUNA Nitrate Sensor | Seaglider Monitoring Status | [186] |
| 2005 | Spain | CSIS-SOCIB | Slocum G2/G3 iRobot Seaglider | 40-1000m | 9-18months | 0.25-0.35m/s | 0.1-0.2m/s | 3-4kg | CTD, Optical, acoustic, and chemical sensors | Glider Tracking | [187] |
| 2006 | Australia | IMOS | Slocum, | 200-1000m | 3-6months | 0.35- | 0.15- | 4-6kg | CTD, | ANFOG | [23, 188] |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Seaglider | | | 0.4m/s | 0.25m/s | | Dissolved oxygen sensor, Irradiance sensor | | |
| 2016-2019 | France | AGLIMMS | Seaglider | 40-1000m | 2-4months | 0.25-0.5m/s | 0.1-0.25m/s | 2-5kg | CTD, PAM | Coordinate UG Fleet | [89, 191, 192] |
| 2017-2023 | China | University of Tianjin | Petrel-II | 1000-1500m | 3-7months | 0.5-1.0m/s | 0.2m/s | 8kg | CTD, Ocean turbulence sensor, Chlorophyll, Fluorometer | | |

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As early as the 1990s, the Autonomous Ocean Sampling Network (AOSN) led by the U.S. Navy Research Institute was studied abroad. The network brings together a variety of ocean observation platforms, indicating that the research on UG networking is officially launched. The network operating system includes data and sensors collected by intelligent and adaptive platforms, which transmit information to shore-based platforms in real-time and assimilate it into numerical models to create four-dimensional domains and make predictions. The purpose of the study is to use a network to observe and detect marine characteristics and marine phenomena in a wide range of offshore and coastal areas based on a single machine. In 2000 and 2003, the first and second phase experiments of ASON were carried out. The second phase experiment of AOSN (AOSN II) was carried out in Monterey Bay. Five Spray gliders were used to observe the scale and mode of the California ocean current system. The last 10 Slocum shallow sea gliders were equipped with fluorometers and photosynthetically active radiation sensors on the basis of Spray measurement parameters, mainly to observe cold water plumes and their related structures. By designing reasonable allocation of control strategies, the observation and data prediction ability of UGs were improved. In August 2006, the ASAP research was carried out on the basis of AOSN-II to achieve efficient index sampling of multiple UGs [27]. In the same year, Godin et al. created and developed a Collaborative Ocean Observing Portal (COOP) in the ASAP field experiment, which allows distributed investigators to operate the ocean observing system collaboratively. The future ocean observing system is planned and the improvement of ASAP is proposed [174]. In addition, how the glider fleet covers a large area of dynamically changing oceans with different fleet has also been studied accordingly.

The ASAP experiment was carried out in Monterey Bay, with a total of 4 Spray gliders and 6 Slocum gliders. The periodic upwelling of the cold current in the northwest of Monterey Bay was investigated. In the experiment, the GCCS is used to optimize the relative distance and fleet between UGs. Through the ASAP test, the multi-UG, as a distributed and mobile autonomous sampling network of marine parameters, has shown excellent advantages and broad prospects in the sampling of marine environmental parameters. Paley et al. developed the GCCS. GCCS is a modular, cross-platform software suite, which realizes the feedback control law of glider fleet coordination. The three main modules of the GCCS are the planner (real-time controller), simulator (as a control test bench), and remote input/output (IO) modules. The GCCS was tested at sea in Buzzards Bay in March 2006. The ASAP experiment demonstrated the capabilities and limitations of the GCCS in the actual high-current deployment of gliders [146].

In 2010, Schofield introduced the engineering significance of UG networking observation shore-based systems in the field of ocean observation abroad. Through the experience of glider networking expansion in the past five years, it is shown that the UG networking shore-based platform can meet the potential of national needs to a certain extent [147]. In the same year, Manley et al. summarized the design and performance of the wave glider, introduced the research of the wave glider in the engineering sea test, and proposed the application of the acoustic detection modulator in the wave glider. The purpose is to propose a new type of UG to achieve the connection between the seabed system and the shore base [71]. In 2010, Leonard et al. conducted an ASAP experiment in Monterey Bay, California, and established a full-scale AOSN. Combined with the newly developed coordinated motion control technology of multiple UGs, they finally demonstrated an innovative ocean sampling tool and provided a theoretical basis for robots in important fields of integrated coordinated motion control and adaptive sampling [28]. In recent years, the research on the shore-based system of UGs has gradually received attention at home and abroad. In 2021, Feng et al. reviewed the development plans of UUV, underwater preset equipment, underwater shore-based monitoring network, and other underwater unmanned equipment abroad, which provided a theoretical basis for the further development of the shore-based system of UGs [193]. The most innovative point of the AOSN-II test is to form a triangular fleet of three Slocum gliders and use the marine characteristics of the fleet to perform adaptive sampling. The effectiveness of the adaptive control strategy for the glider fleet is verified by three fleet tests [175]. In 2025, Ventola et al. autonomously redesigned the Slocum glider to enhance its propulsion integration capabilities. Experimental results demonstrated that this upgrade improves gliding efficiency by over 30%, while also ensuring robust performance in complex environment such as ice-covered regions and abyssal depth [194].

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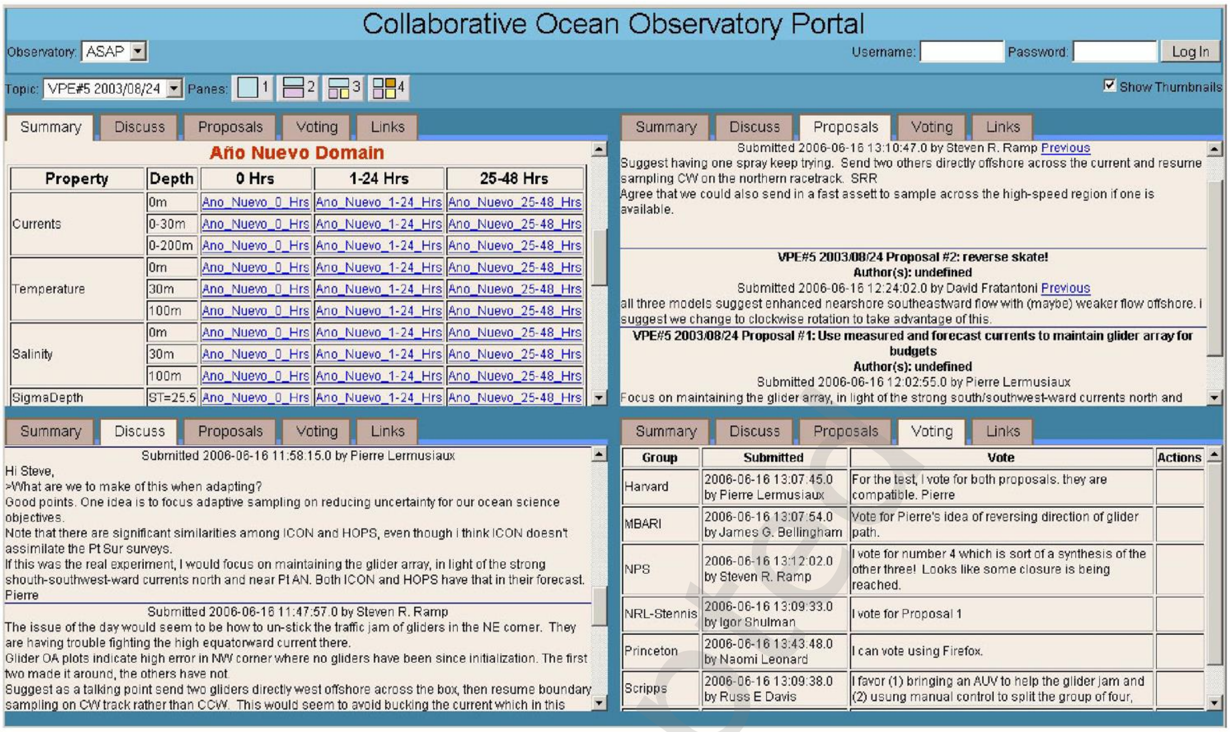


**Figure 6** The operation interface of the COOP system developed in the ASAP test

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The offshore underwater continuous monitoring network (PLUSNet) is a semi-autonomously controlled submarine fixed underwater mobile networked facility consisting of multiple underwater submersibles (mobile communication nodes) carrying semi-autonomous sensors. These submarines can communicate with each other and make decisions without human instructions, thus performing a variety of functions, closely monitoring and predicting the marine environment. The purpose is to detect, classify, locate, and track quiet conventional submarines through networked collaborative work, which can provide surveillance capabilities for anti-submarine warfare in an area of about 104 square kilometers. In 2006, the United States began to develop PLUSNet, which includes thirty-five nodes: 1 "seahorse" and 6 Blue Wing-21 AUVs, 1 XRay UG, eighteen "ocean glider" mobile nodes, and 9 fixed element nodes [176-177].

The main tasks of the PLUSNet UG network system are hydrological measurement, seabed imaging, ocean noise and underwater target noise detection, and generating a coastal environment situation map. The main functions of the network system include: deploying fixed and mobile sensors on the seabed; communication between sensors by means of acoustics and

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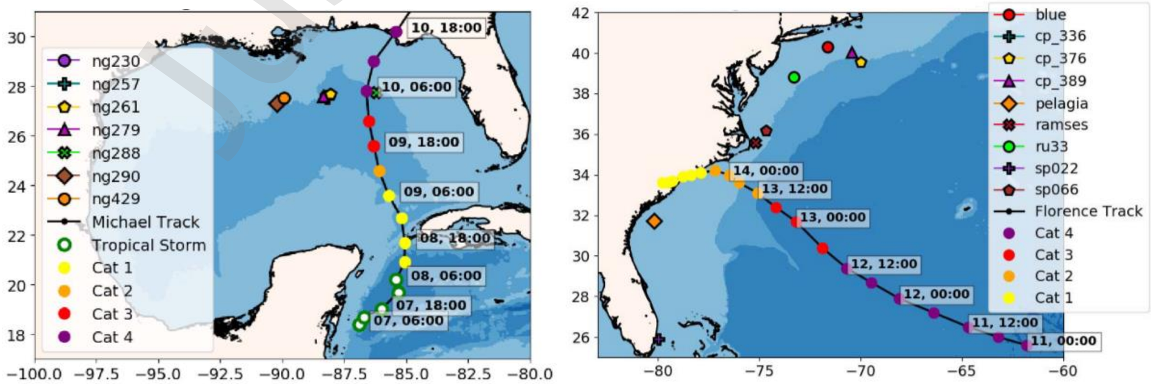
radio; monitoring the sensor's own state and system state; continuous monitoring of the environment; adjusting the number and location of sensors to obtain the most useful information or replace faulty sensors. The expected mission area of the system is 50×175km or 220×330km, and the actual size depends on the operational requirements. The combat network can continuously detect and monitor for about 40 days. The system is mainly deployed in the shallow water area near the southeast coast of Zhoushan and the channel of submarines around Taiwan, including the west of Okinawa, Miyako Strait, Taiwan Strait, and Bashi Strait.

In 2006, the European Gliding Observatories Network (EGO), also known as Everyone's Gliding Observatories Network, was formed by marine scientists from the United Kingdom, France, Germany, Italy, Spain, and Norway. The main purpose is to coordinate the research of glider applications, establish multi-level cooperation on a global scale, and achieve long-term ocean observation missions in different ranges, such as global, regional, and offshore. Subsequently, oceanographers from Australia, Canada, South Africa, and the United States also joined in. So far, more than six hundred gliders have successfully performed various ocean observation tasks and completed the collection of more than 2000000 profiles. In July 2010, the COST Action ES0904 "EGO" project was launched, which established international cooperation at the scientific, technical, and organizational levels to promote the application of gliders in continuous ocean observation. From 2005 to the end of April 2014, EGO deployed approximately three hundred gliders for various ocean observation missions [22]. Figure 21 shows the glider EGO observation.

The GROOM (Gliders for Research, Ocean Observation and Management) project started in 2011 and ended in 2014. Its purpose is to assess the needs and provide a roadmap for the construction of glider components in the European Ocean Observatory network. In this project, a distributed glider port network was established in the European Seas and other sea areas to coordinate the glider observation tasks. In order to make up for the gaps in the existing observation network and operation cycle model, a Mission Planning and Analysis Tool (MPAT) was developed to design the optimal sampling topology of the glider, and the observation data range of the glider was expanded through new sensor testing. The EGO project also refined the infrastructure design part of the EU cooperation project GROOM. It solves the design and research problems of infrastructure in all fields of science and technology. In addition, the feasibility of applying acoustic technology to glider navigation and data transmission in extreme environments is evaluated, which provides important supplementary information for the existing Global Ocean Observing System (GOOS), fills the gaps left by the current ocean observation systems in the global, regional and coastal observation ranges, and promotes ocean basic research and ocean observation research.

IOOS (Integrated Ocean Observing System) was proposed in 2002. It is a cross-system federal program hosted by the United States Oceanic and Atmospheric Administration and is a national organization. Its purpose is to establish a comprehensive marine observation system, through which to enhance the understanding of ecosystems and climate, protect the sustainable use of marine biological resources, reduce the adverse effects of natural disasters and environmental changes on people, and strengthen the support for maritime commercial and transportation activities. IOOS attaches great importance to the role of gliders in the marine observation network. In August 2012, it initially proposed the "National Glider Network Plan", established the UG data center (DAC), adopted a unified glider data format, and shared observation data [21, 48, 67, 178, 179, 181]. IOOS observation system has established three conventional observation networks of continuous climate ecological observation area, crisis rapid response area, and hurricane intensive area. A hurricane-oriented UG observation program was organized in conjunction with the U.S. Department of Commerce, NOAA, and others. Figure 23 shows the IOOS glider network plan, and Figure 24 shows the UG observation plan.






**(a)** **(b)**

**Figure 7 (a)** Glider deployments in the GoM during hurricane Michael 2018 **(b)**Glider deployments in the MAB and SAB during hurricane Florence 2018 (Reproduced with permission from Ref. [21] ©2019 OCEANS 2019 MTS/IEEE SEATTLE)

In order to effectively manage and rationally optimize the glider network, the corresponding shore-based control platform has also been studied while the glider network is established abroad. In order to monitor the glider task in real-time, the Spanish PLOCAN mechanism has established a shore-based control station based on the dynamic map of the task path. The control station can display data in real-time, and staff can download relevant data from the control station. Users can display the navigation information and parameter information of each glider during the mission as needed. In 2015, Javier et al. introduced a shore-based ocean test site of PLOCAN and discussed the development of UGs in the field of marine science and technology in the sea test site. The establishment of a PLOCAN shore-based system contributes to the subsequent development of UGs [185]. The PLOCAN glider task control interface is shown in Figure 25. [182 -184]

**Figure 8** A Slocum G2 operated by PLOCAN (Reproduced with permission from Ref. [182] ©2018, IEEE)

The Scientific Research Council (CSIC) of the Spanish National Investigative Committee has designed a shore-based control station for tracking gliders, which can track the gliders of CSIC and SOCIB [187, 188].

The Italian National Institute of Oceanography and Geophysics (OGS) has also developed a shore-based control system for glider navigation and data display. The operator can monitor the status of the Seaglider glider and navigate it [186, 189].

IMOS (Integrated Marine Observing System) is a national cooperative research organization established by the Australian government in 2006. The purpose of this system is to develop a comprehensive national marine multidisciplinary observation system [190]. It includes access to and provision of free, open, and timely access to data infrastructure for use by Australian and global marine science communities. IMOS observations are guided by scientific planning and are carried out collaboratively across the scientific community with input from government, industry, and other stakeholders [148]. As a subsystem of IMOS, ANFOG (The Australian National Facility for Ocean Gliders) is mainly responsible for the operation and maintenance of a fleet of UGs such as Slocum and Seaglider. Among them, the Slocum glider is mainly distributed in the continental shelf waters, and the Seaglider glider is used to monitor deep-sea fish. Each glider in the ANFOG system is equipped with CTD, a three-parameter optical sensor, and dissolved oxygen sensor, which is responsible for the measurement of the Australian continental shelf and coastal waters. It has made significant contributions to the study of marine phenomena in the area, such as the physical and biogeochemical characteristics of the eddy, internal tides and sediment resuspension, and the impact of the East Australian Current on the dynamics of the continental shelf. So far, the ANFOG system has deployed more than 180 Slocum gliders and 40 Seaglider gliders, performing more than 225 glider observation missions and sailing for more than 6400 days [23].

AGLIMMS project is Acoustic Gliders Mission Management System. Three complementary partners were involved in the French AGLIMMS project: Alseamar (project lead) has operated SeaExplorer (Figure 28) since 2017; ONERA has done extensive research on UUV cooperation since 2007; CentralWeb has developed big data management and web-mapping systems. AGLIMMS's goal is to create a centralized MMS to effectively coordinate an UG fleet tasked with conducting physical, chemical, biological, and/or acoustic measurements over a large three-dimensional sea area. It also introduces the components and tests of the developed planning and monitoring system, which is integrated into a global centralized architecture, and describes a 12-day sea experiment using three SeaExplorer gliders of Alseamar in the Mediterranean Sea in November 2019 [191], MMS is concentrated on a network-based platform called GLIMPSE (Glider Mission Driving System), allowing multiple users to prepare, monitor and analyze glider missions [89, 192].

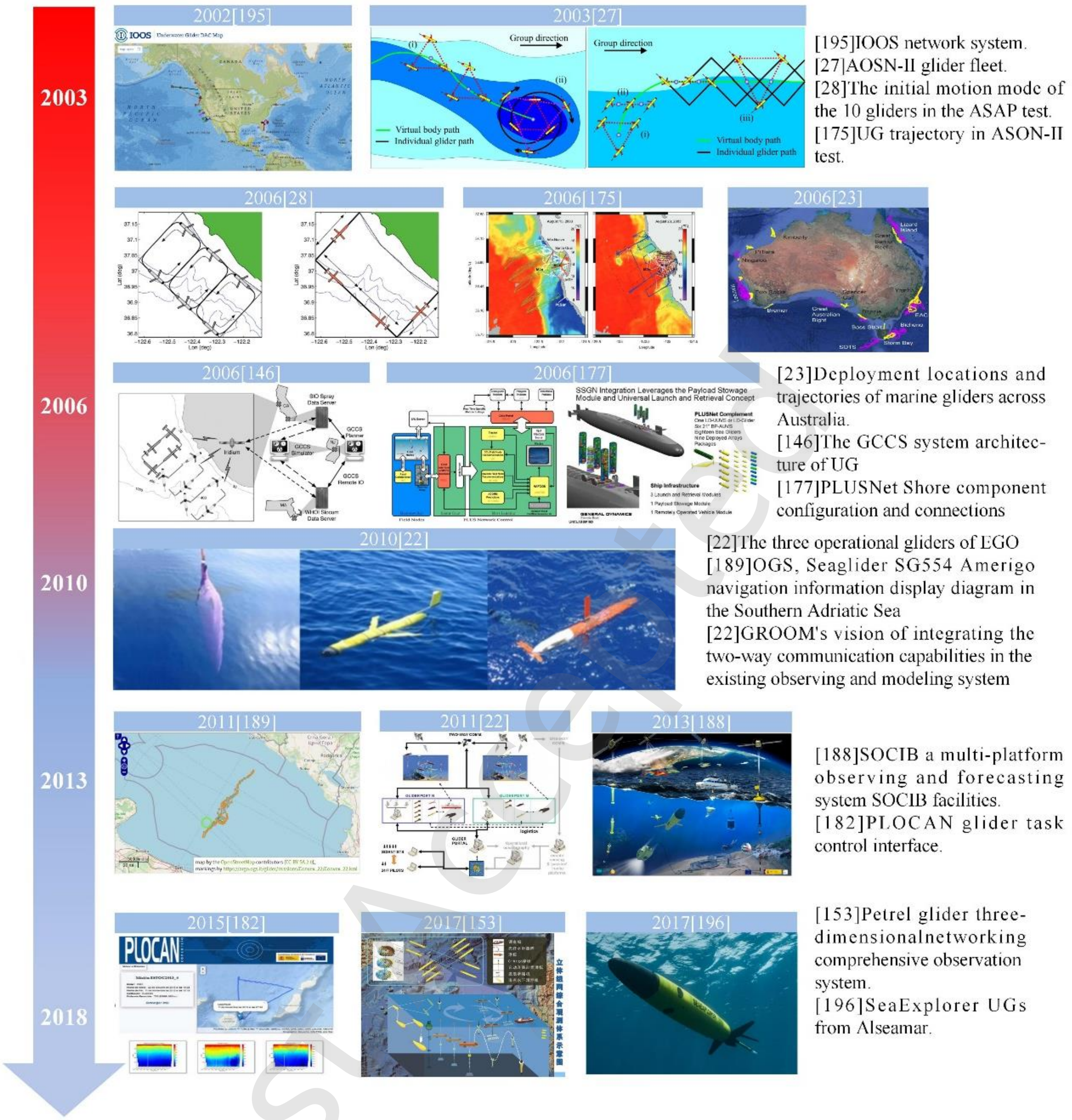
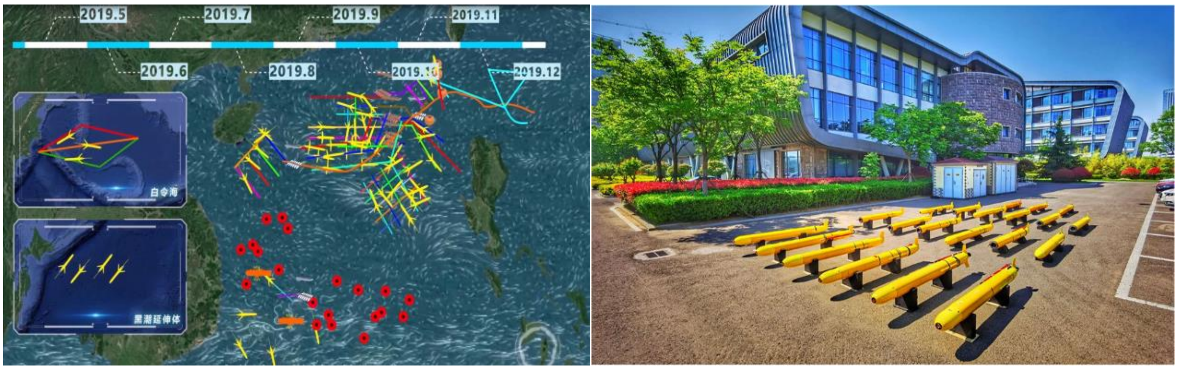



**Figure 9** Representative shore-based control platform of UG fleet. The images are reproduced with permission by copyright as follows: Ref. [28] ©2010, Wiley Periodicals, Inc.; Ref. [27] ©2003, Proc. 13th Int. Symp. on Unmanned Untethered Submersible Technology (UUST); Ref. [175] ©2009, Elsevier Ltd.; Ref. [146] ©2008, IEEE; Ref. [177] ©2006, University of Washington Tacoma Submarine technology symposium; Ref. [22] ©2013, EGU General Assembly); Ref. [195] ©2026, IOOS UGs DAC maps; Ref. [182] ©2018, IEEE; Ref. [188] ©2019, The Authors; Ref. [189] ©2021, OGS, CC BY-SA 2.0; Ref. [23] © 2017, The Oceanography Society; Ref. [196]. ©2017, ALSEAMAR; Ref. [153]. ©2018, CNKI.

On August 10, 2019, the "Xiangyanghong 01" scientific research ship set sail from Qingdao's port to carry out China's tenth Arctic expedition. Three UGs were equipped with temperature, salinity, depth, and dissolved oxygen sensors. Through 22 days of network observation, the data of water bodies and biochemical elements in the Arctic Sea area were observed. The "Petrel" glider obtained continuous and high-density hydrological and biochemical observation data in the east-west direction of the Bering Sea high seas and successfully completed the inspection task.

**Figure 10** Stereoscopic networking comprehensive observation system.

In May 2019, Qingdao Marine Science and Technology Pilot National Laboratory Tianjin University, and other units launched an ocean network observation plan with a total of seventy-four unmanned equipment, including "Petrel" UG, 2 wave gliders, HM-2000 buoys, real-time transmission submersibles, etc. It is the largest heterogeneous integrated observation unmanned system in China so far. The observation area is centered on the central and northern parts of the South China Sea, radiating the Luzon Strait and the Kuroshio Extension, covering a sea area of 1.05 million square kilometers from the air-sea interface to a water depth of 4000 meters. During the networking period, there are 45 simultaneous observation equipment in the network. In 2021, Wang et al. optimized the configuration of the Petrel-L glider, reducing the loss in gliding distance due to biofouling to just 7.11% [197].




**(a)** **(b)**

**Figure 11** (a) Ocean network observation; (b) Petrel glider

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## 6 The Future Development Trend of UG Fleet Technology

Based on current research in underwater gliders, three specific future directions for underwater glider swarms are proposed:

Resilient Event-Driven Swarm Algorithms for Fault-Tolerant Collaborative Fleet. Underwater gliders operate within highly constrained communication windows, as data transmission is restricted to intermittent surfacing phases. During extended missions, such as cross-seasonal ocean circulation monitoring and collaborative temperature-salinity (T/S) profiling, maintaining formation cohesion during prolonged communication blackouts is critical, as deviations can otherwise escalate to tens of kilometers. To sustain swarm integrity under extremely low communication probabilities, an event-triggered strategy is employed: gliders actively surface to synchronize data when formation error exceeds a predefined threshold, ensuring resilient and adaptive data transmission. Furthermore, by leveraging oceanic phenomena like currents and eddies, the algorithm optimizes path planning for multi-layer positioning. This approach not only minimizes power consumption but also harnesses environmental dynamics to facilitate glider propulsion and navigation.

Self-Healing Heterogeneous Formation Framework for Cascading Failure Mitigation. To address cascading network collapses precipitated by individual glider malfunctions, such as buoyancy engine failures or communication module damage, this framework introduces a self-healing mechanism for heterogeneous formations. By implementing an adaptive topology reconfiguration strategy, the swarm maintains mission-task allocation and environmental sensing capabilities even when 30% of the constituent gliders are compromised. The framework further incorporates a robust performance evaluation scheme to assess mission effectiveness across varying swarm scales and failure rate scenarios, ensuring operational continuity in unpredictable maritime environments.

Energy-Aware Opportunistic Reconfiguration via Alternating Formation Strategies. In resource-constrained environments where mid-mission replenishment is infeasible, maximizing the operational longevity of the swarm is paramount, particularly within thermocline and open-ocean regions. A differential energy consumption model is established to provide real-time predictive analytics of energy depletion curves for all swarm members. To mitigate the disparate energy costs associated with different operational roles, a dynamic leader-follower rotation mechanism is introduced; this allows the lead glider to periodically swap roles, subsequently operating at a reduced frequency to minimize passive power drainage. During transit, the system identifies high-energy-expenditure zones, characterized by intense thermoclines or powerful currents, and triggers a temporary formation dissolution. Members then transition to individual energy-optimal trajectories and converge at designated spatio-temporal coordinates for formation reconstitution, effectively bypassing high-resistance oceanic features.

Prospectively, the confluence of these technological vectors will catalyze a paradigm shift in oceanic exploration. Emerging priorities will center on holistically integrated systems interoperability, merging adaptive governance, fault-tolerant networking, and energy self-sufficiency into unified operational ecologies. Anticipated developments emphasize environmental plasticity, empowering fleet to traverse volatile marine domains with autonomous decision-making sophistication. The maturation of cooperative localization and self-repair mechanisms will cement fleet matrices as indispensable instruments for abyssal resource prospecting and biosphere monitoring.

Collectively, UG networks herald an era of marine cybernetic ecosystems, where distributed cognition and transdomain interoperability expand the frontiers of oceanic observation. As these architectures evolve, their capacity for sustained operation in extreme conditions will unveil novel frontiers for scientific inquiry and ecological governance, contingent upon advancing systemic antifragility and operational synchronicity.

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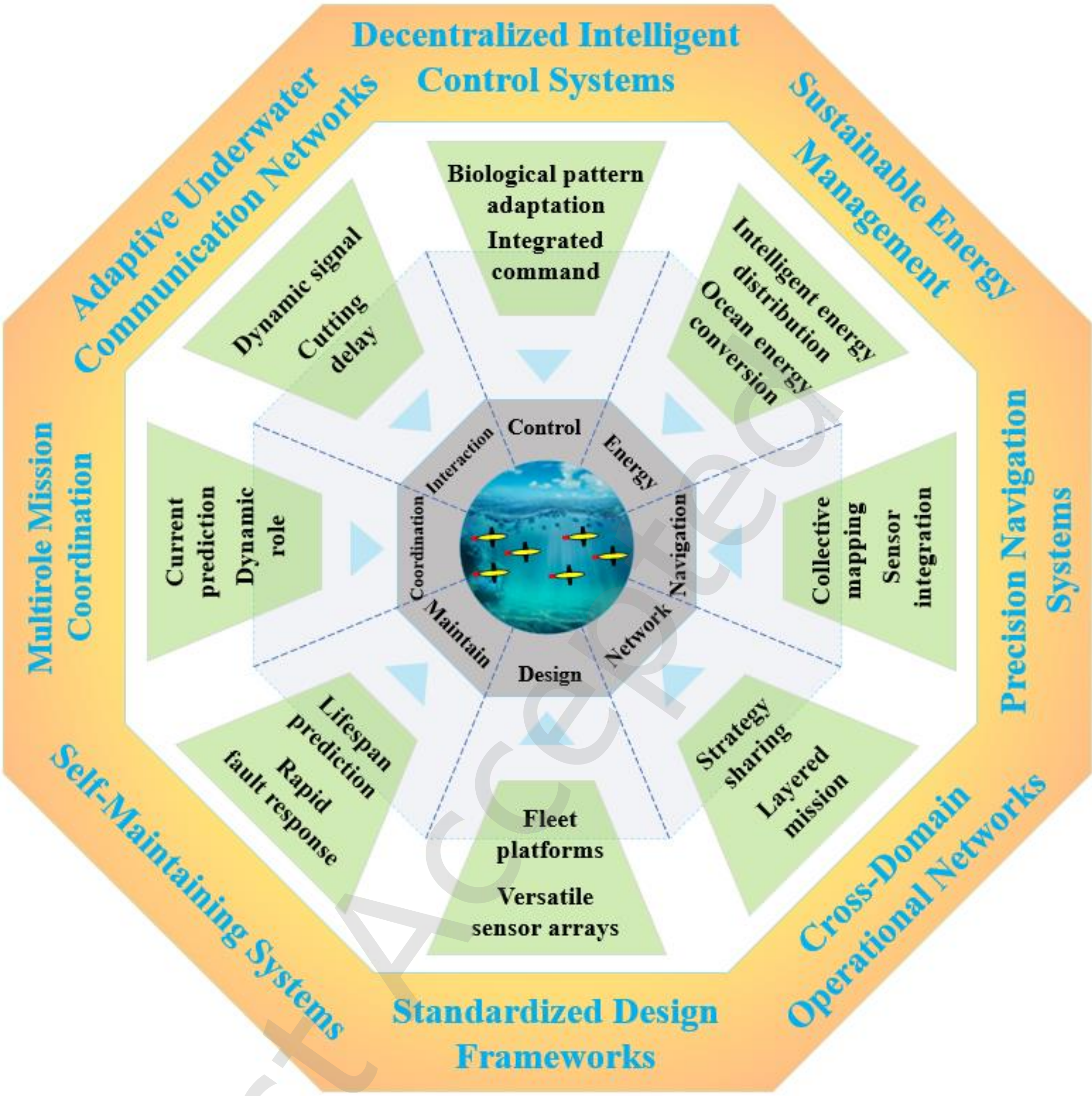


**Figure 12** Future critical development trend of UG fleet technology.

## 7 Conclusion

UG fleet technology has evolved from individual platforms to coordinated intelligent networks capable of multidimensional ocean observation. Two decades of development in coordination algorithms, communication systems, energy management, and navigation have established UG fleets as essential tools for monitoring dynamic marine phenomena—including mesoscale eddies, typhoons, and Kuroshio Current variations. Bioinspired coordination, adaptive control, and hybrid communication protocols enable reliable operations in satellite-denied environments under challenging hydrodynamic conditions.

These fleet have transformed marine research through high-resolution thermohaline mapping, acoustic monitoring, and ecosystem assessment. Campaigns in the South China Sea, Kuroshio region, and Mediterranean have successfully reconstructed 3D ocean structures, tracked submesoscale eddy, and quantified turbulent energy dissipation. Technological innovation in complex underwater environments demands resolution. As path planning optimization algorithms continue advancing, multi-robot swarm theories warrant systematic investigation and strategic adaptation for UG formation.

UG fleet now connect oceanographic theory with marine engineering practice. Their integration with satellites, surface vehicles, and seabed sensors marks a critical step toward comprehensive ocean understanding and sustainable management.



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**Author contribution statement**

Bing He: investigation, formal analysis, visualization, writing — original draft. Run-Feng Zhang: project administration, supervision, writing — review & editing. Rui-Ze Pan: conceptualization, methodology. Ju-Tao Wang: funding acquisition, project administration, supervision, writing — review & editing, resources. Xu Wan: conceptualization, methodology. Ji-Jia Sang: formal analysis, visualization. All the authors have approved the final manuscript.

**Data availability**

Not applicable.

**Declaration of competing interest**

Runfeng Zhang is the employee of Tianjin Wybotics Inc.. The other contributing authors report no conflicts of interest in this work.

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**Use of AI statement**

None.



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