



Research progress and prospects of gliding robots applied in ocean observation

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Abstract

Ocean observation is the prerequisite for the human to cognize and develop the ocean. Most autonomous ocean-observation platforms (AOOPs), for their limited endurance, cannot cope with the further application in large range and long-term marine operations. Gliding robots have become one category of the most powerful platforms in ocean observation for their super endurance, with marine renewable energy acquisition or new driving modes. This paper starts with the comparison of the performance characteristics of several typical AOOPs, and introduces the definition and classification of the gliding robots according to their certain features. The research progresses of each gliding robot to date are discussed, including underwater glider, wave glider and multifunction hybrid glider. The prospects for the future development of related technologies in gliding robots are also represented in this paper, which will provide a reference for novel AOOPs' construction and application selection in ocean observation, based on carrying different sensors.

Keywords Autonomous ocean-observation platforms · Gliding robots · Ocean observation · Endurance · Marine renewable energy

1 Introduction

With the deepening of the marine scientific research, AOOPs are required to have higher performance. On one hand, they

must have certain intelligence to complete the marine data collection automatically following the given instructions, and send the data to offshore monitoring center through wireless or satellite communication mode. On the other hand, for these platforms, the strong endurances are principal elements in completing large range and long-term marine operations. The contradiction between their finite energy (mostly equipped with batteries) and strong endurance has always been a limiting factor for the latent potential of the application in ocean observation (Tian and Yu 2019). After two or three decades, various types of AOOPs began to (emerging in large numbers) proliferate and their intellectualized level has been promoted with the development of ocean science and technology. The different performance characteristics of some typical AOOPs are summarized in Table 1, such as manned submersible, AUV (autonomous underwater vehicle), ROV (remote operated vehicle), underwater glider, and wave glider (Roberts and Suttons 2006; Chen 2014).

From Table 1, it can be seen that traditional underwater vehicles, such as manned submersible, AUV, ROV, have endurance (main working time and working range) of hours, days, even months, but underwater glider and wave glider have endurance of years, which is closely related to their marine renewable energy applied or new driving modes. The

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Table 1 Summary table of performance characteristics of different AOOPs

AOOPs	Working time	Working range	Measured water	Cost	Example pictures
Manned submersible	Hours to days	Few to tens of kms	Surface and deep water	Very high	
AUV	Hours to days	Tens to hundreds kms	Deep water	High	
ROV	Days to months	Tens to hundreds kms	Deep water	High	
Underwater glider	Weeks to years	Hundreds to thousands kms	Deep water	Low	
Wave glider	Months to years	Thousands to tens of thousands kms	Surface water	Low	

AOOPs (such as manned submersible, AUV, etc.), are generally equipped with the batteries as their power supply, so their endurance is mainly significantly affected by the battery capacity. The power consumed by ROV, is provided by the mother ship over the tether, so the length of the tether greatly affects the operating range of the ROV. Meanwhile, the adoption and logistics of mother ships will increase the application costs.

However, underwater glider was driven by buoyancy change, and can achieve zigzag movement in the ocean vertical profile. Simultaneously, wave glider is a new type of unmanned surface vehicle, obtaining the driving force from the wave energy and supplying the electric energy through the solar power. In addition, these two types of AOOPs have become important ocean-observation platforms, due to their advantages of strong endurance.

2 Definition and classification of the gliding robots

Compared to the traditional propeller-driven ocean robots (such as AUV and ROV, etc.), the gliding robots applied in ocean observation are one category of ocean robots with no external propeller, and get the driving force through the interaction between their own wing plates (or shell) and water. When the gliding robots move at a velocity V relative to the water (under the wave excitation or buoyancy change), a certain attack angle α will be formed between the velocity and water. So the wing plates (or shell) will be subjected to hydrodynamic lift L and drag D , and the combined effect of these two forces will always generate a horizontal forward

force, called driving force F_x , as shown in Fig. 1. Under the action of the driving force F_x , the gliding robots can keep moving forward and computation formulas of each force can be expressed as follows (Georgiades et al. 2009; Tian et al. 2014a, b):

$$L = 0.5\rho V^2 S_w C_L(\alpha), \quad (1)$$

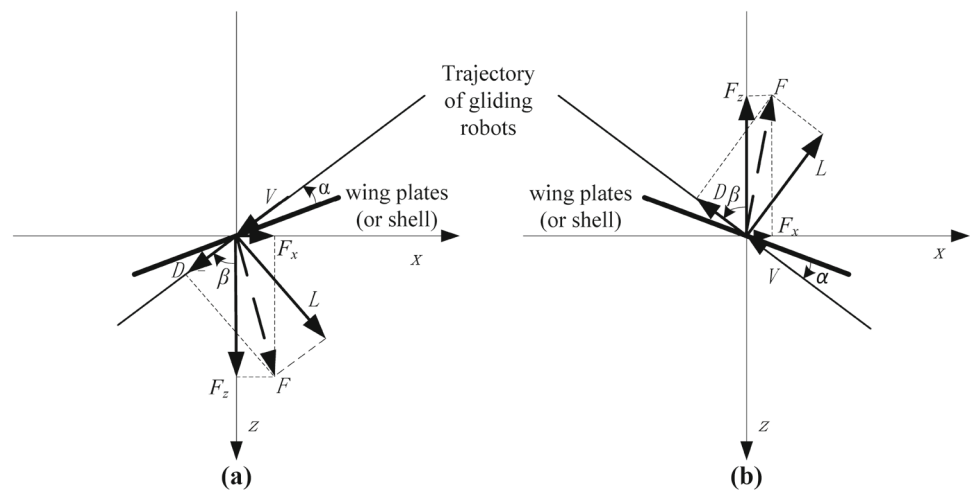
$$D = 0.5\rho V^2 S_w C_D(\alpha), \quad (2)$$

$$F_x = D \sin \beta + L \cos \beta, \quad (3)$$

where, V is the water velocity relative to the wing plate (or shell), β is the angle between the velocity V and the Z axis, ρ is water density, S_w is the area of wing plate or shell, α is the attack angle, $C_L(\alpha)$, $C_D(\alpha)$ are the lift coefficient and drag coefficient respectively.

The current types of gliding robots applied in ocean observation generally consist of three categories: underwater glider, wave glider and multifunction glider. On the structure, the underwater glider is a monomer structure, while the wave glider and multifunction glider is a couple or multi-body structure. In the aspect of energy acquisition, underwater glider has three types of electric-driven, solar-powered, and thermal energy; wave glider only uses wave energy and solar energy as its own energy source; and multifunctional hybrid glider, as a new combination of the two gliders mentioned above, can make the comprehensive utilization of wave energy, solar energy and buoyancy-driving mode. From the perspective of technology maturity, the underwater glider appeared first, followed by wave glider. These two robots have been tested and verified by a large number of marine

Fig. 1 Motion principle of gliding robots: **a** force diagram when gliding robots rises; **b** force diagram when gliding robots falls



experiments, and have been commercialized. Multifunction glider, with more diverse functions, is still in the conceptual design stage in recent years, based on the technology of underwater glider and wave glider.

3 Research progress of gliding robots

3.1 Underwater glider

The original concept of underwater glider was proposed by Stommel in 1989, as a buoy gliding to investigate marine environment (Stommel 1989). Its movement function is realized by the cooperation of the internal buoyancy adjustment subsystem and attitude control subsystem (including roll control subsystem and pitch control subsystem), with zigzag and spiral motion trajectory. As shown in Fig. 2, when the underwater glider receives diving instruction from ashore monitoring center through the wireless or satellite communication, the motor in pitch control subsystem will drive the internal mass (usually the battery) to move forward a certain distance, resulting in its center of gravity forward, with the state of bow down and tail up. Meanwhile, the oil pump in buoyancy adjustment subsystem will press oil from outside bladder to inside bladder, resulting in its displacement volume becoming smaller, so its buoyancy will be less than gravity and it will dive in the water. During the diving process, hydrodynamic lift and drag force will be generated due to the attack angle α between its wing plates (or shell) and water flow, and the underwater glider will get a forward driving force from the horizontal component of hydrodynamic lift and drag force. When the underwater glider glides to a certain depth, the motor in pitch control subsystem will drive the internal mass (usually the battery) to move backwards a certain distance, with the state of bow up and tail down. Meanwhile, the oil pump in buoyancy adjustment subsystem

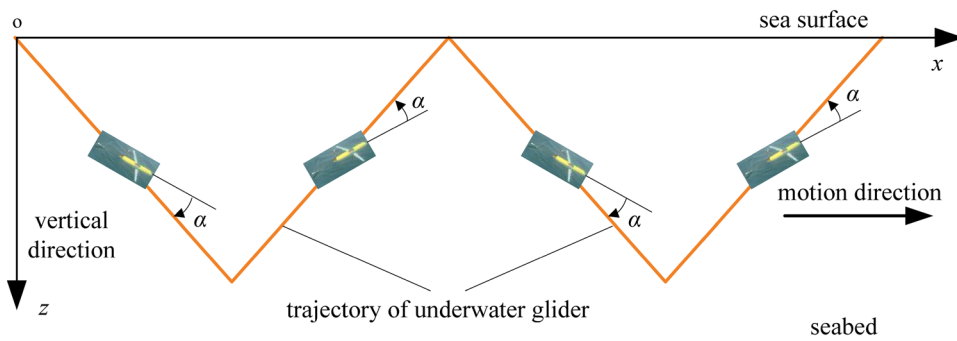
Table 2 Main parameters of typical underwater glider (Rudnick et al. 2004; Wood and Mierzwa 2013)

Underwater glider	Spray	Seaglider	Slocum
Length (m)	2	1.8	2.15
Diameter (m)	0.2	0.3	0.22
Net weight (Kg)	51.8	52	52
Average velocity (m/s)	0.25–0.3	0.25	0.35
Depth capacity (m)	1500	200–6000	30–1500
Endurance	330 days, 4800 km	10 months, 4600 km	1 year, 6000 km
Carrying capacity (Kg)	3.5	5	4
Cost	\$50,000	\$70,000	\$70,000

will press oil from inside bladder to outside bladder, making the underwater glider come-up. During its come-up process, the generation of driving force is similar to the diving process above. It can be seen in Fig. 2, that no matter in the come-up or diving process of underwater glider, the direction of the driving force is always forward.

After decades of underwater glider's development, many research achievements have been made around the world. The United States has developed Spray, Seaglider, Slocum, and other types of underwater glider (Eriksen et al. 2001; Sherman et al. 2001; Webb et al. 2001), with main parameters as shown in Table 2. In addition, France, Canada, Japan, and South Korea and China have also carried out research work and made important progress related to underwater glider (Yu et al. 2013; Zhang et al. 2013). With the different sensors deployed on gliders, it has been widely applied in many aspects of the marine scientific research, such as marine climatology research (Rudnick et al. 2017), oceanic

Fig. 2 Motion principle diagram of underwater glider



parameters measurement and marine data acquisition (Vincent et al. 2018; Zhang et al. 2018), marine wind speed estimation (Cauchy et al. 2018; Cazau et al. 2019), internal solitary waves observation (Todd 2017), kuroshio with an anticyclonic eddy (Liu et al. 2019), observing irregularly shaped warm eddy (Qiu et al. 2019), mapping the underside of an iceberg (Zhou et al. 2019), etc. According to the different driving energy sources, underwater gliders can be divided into three types of electric-driven, solar-powered and thermal underwater glider, but their basic motion principles are completely similar.

3.1.1 Electric-driven underwater glider

At present, electric-driven underwater gliders are the most mature in the technology and market, and the most widely used in ocean environment observation, such as Spray, Seaglider etc. The high energy density batteries (most lithium battery) was usually used as its power supply for the entire system, including electronics and motors of the buoyancy control system and attitude control system, electronic control system and communication system etc. Figure 3 shows that seaglider has main battery pack and forward battery pack as its electric energy supply, where the main battery pack was also used as internal mass to adjust its center of gravity to control its attitude (Osse and Eriksen 2007). With the progress of battery technology, their endurance has got improved, roughly in the weeks and months.

3.1.2 Solar-powered underwater glider

Solar energy is taken as the inexhaustible, renewable, green and clean energy (Letcher 2008), which generally refers to the radiant energy of sunlight. The solar energy applied in underwater glider is helpful to solve the problem of the power supply. Solar-powered underwater gliders can transform the solar energy into electric energy through their own solar photovoltaic system, and store the electric energy in the battery, which will significantly improve their endurance to successfully complete the large range and long-term ocean missions.

Due to their unique driving principle and motion mode, Solar-powered underwater gliders can only achieve the conversion of solar energy to electric energy at the off working state. Firstly, it is necessary to monitor the power status of the gliders' battery by the ashore monitoring center. Then when their batteries are insufficient and need to charge, the solar-powered underwater gliders will receive the order to stop diving in the water again, and adjust their attitude to the level state to achieve charging on the water surface.

Considering the influence of laboratory environment on the solar power supply system, an experimental platform of solar-powered underwater glider, SORA, was established by Masakazu Arima, etc. from Osaka Prefecture University in Japan, which can demonstrate the possibility of solar energy application in the underwater glider (Arima et al. 2011; Arima and Tonai 2012), as shown in Fig. 4a. Whereafter, to monitor shallow coral reefs, a solar-powered underwater glider, Tonai60, was developed by Arima's team. This platform is capable of diving 60 m and can able to obtain water environment information (water depth, temperature, salinity, etc.) and water quality parameters (chlorophyll, turbidity, etc.), by the sensors on board, such as camera, compass and an environmental data logger (Arima et al. 2014a, b; Arima et al. 2014a, b).

3.1.3 Thermal underwater glider

The thermal energy refers to the thalassothermal energy stored by the temperature difference between surface and deep ocean water. The ocean is irradiated by the sun, with the sea surface (20–30 °C) and the deep-sea (3–10 °C) (Cai 2016). The solar radiative energy rapidly decreases as the ocean depth increases, where only 1% of radiative energy can reach the water with depth of more than 10 m. Considering the glider moving in the ocean vertical profile, the thermal energy can be used as one of the power sources for underwater gliders.

The thermal underwater glider, first developed by Webb Research, uses a thermal engine system to obtain propulsion from the ocean thermocline, which provides an adequate

Fig. 3 Electric-driven underwater glider, seaglider (Osse and Eriksen 2007)

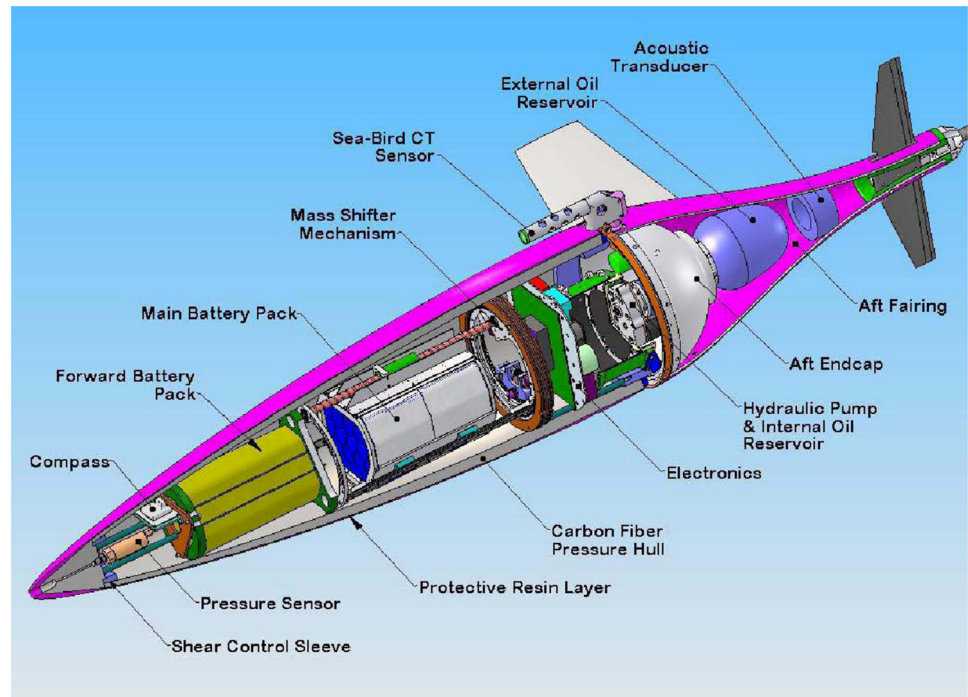
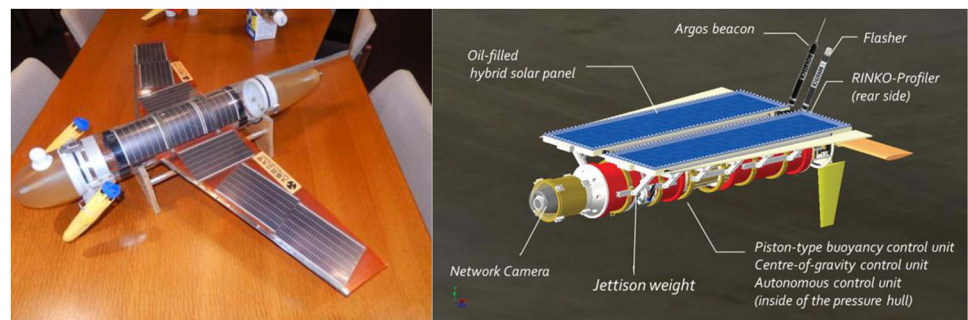


Fig. 4 Solar-powered underwater glider: **a** SORA (Arima et al. 2011); **b** Tonai60 (Arima et al. 2014a, b)



(a)

(b)

change in buoyancy of the vehicle with constant mass to enable it to ascend or descend (Webb et al. 2001). The heat collected by the engine changes the solid–liquid state of the working fluid, which will help the glider achieve a change in volume (or buoyancy). The completion of the thermodynamic cycle is divided into four stages, as shown in Fig. 5

As can be seen from Fig. 5a, the heat engine is in a stable thermal equilibrium state in warm surface water, and the nitrogen gas is compressed. The buoyancy of the vehicle is slightly greater than gravity, due to the expansion of the outer bladder. As shown in Fig. 5b, after the three-way valve is opened, the outer bladder and the inner bladder are connected. The transfer fluid from the outer bladder flows into the inner bladder, and the glider dives with the decrease of buoyancy. When the vehicle reaches the cold water, the working fluid will begin to contract and the transfer fluid will flow into the energy exchanger. As can be seen from Fig. 5c, when

the three-way valve is opened again, the pressurized transfer fluid will flow into the outer bladder and the vehicle will rise with the buoyancy increasing. Figure 5d shows that when the vehicle rises to warm surface water, the working fluid melts and expands to absorbing heat, and the glycol flows to replenish the accumulator. The vehicle returns to the initial state in Fig. 5a.

3.2 Wave glider

As a new concept marine gliding robot, Wave Glider can convert wave energy and solar energy into driving force and electricity respectively, so the problem of its power supply has been thoroughly solved. In 2005, the original concept of wave glider, was firstly proposed by Liquid Robotics Inc (Hine et al. 2009; Manley and Willcox 2010a, b), with multi-body structure (float body, cable and underwater glider body).

Fig. 5 Thermodynamic cycle of thermal underwater glider (Webb et al. 2001). **a** Equilibrium conditions at surface before descent. **b** Descent with heat flow to water. **c** Beginning of ascent. **d** Ascent, heat flowing from water, returned to equilibrium as in **a**

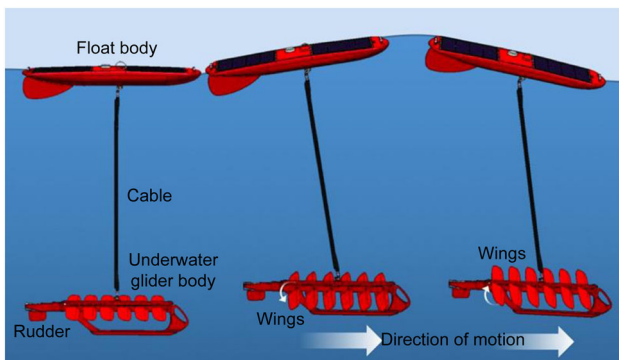
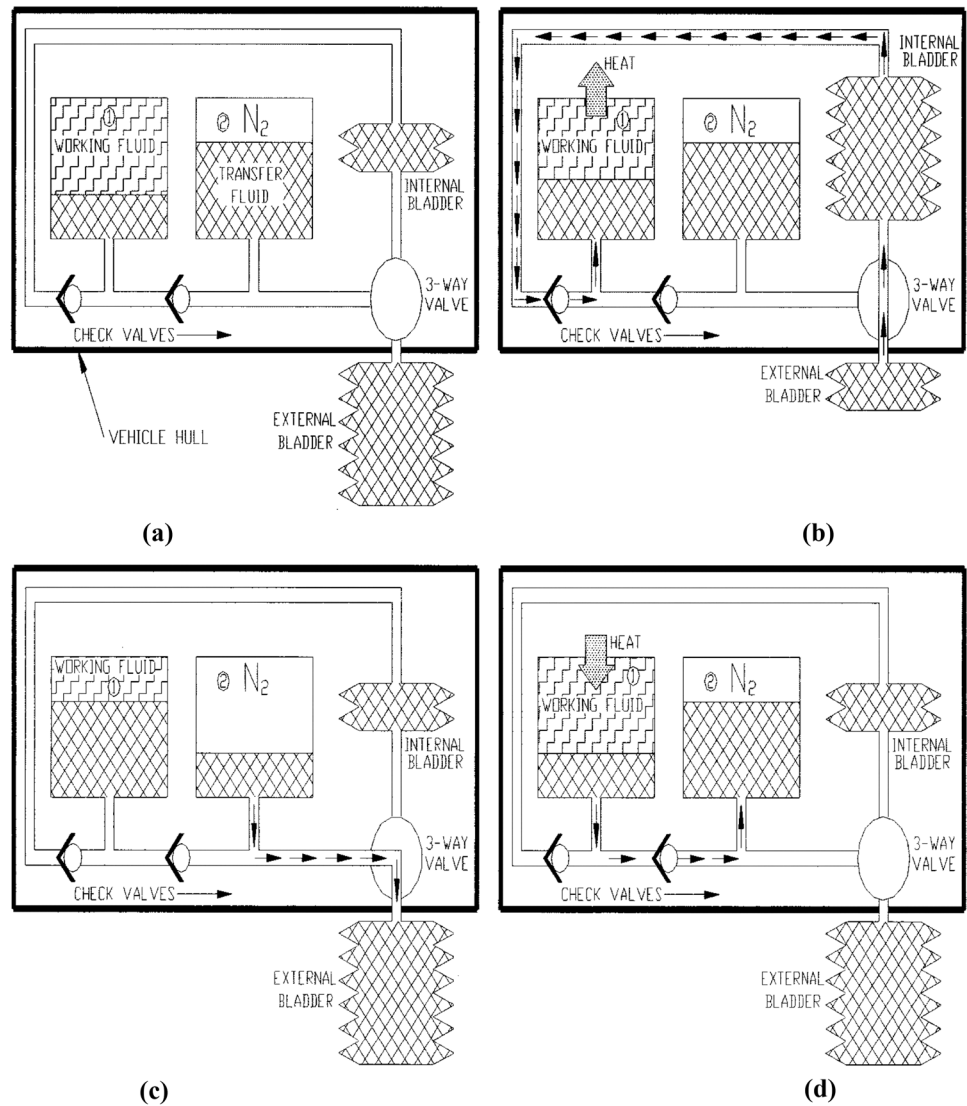


Fig. 6 The structure and motion principle of wave glider developed by Liquid Robotics Inc

Table 3 Main parameters of wave glider developed by Liquid Robotics Inc.

Float (m)	Length: 2.1; width: 0.6
Cable (m)	Length: 6
Underwater glider body (m)	Length: 1.9; width: 0.4
Net weight (Kg)	90
Average velocity (m/s)	0.5 (SS1); 0.6 (SS4)
Endurance	up to 1 year
Battery capacity (W h)	665
Solar panel power (W)	112
Carrying capacity (Kg)	18

The movement principle and main parameters of wave glider can be demonstrated in Fig. 6 and Table 3 respectively, the wave glider’s upper float body rises or falls under the wave

action on the ocean surface. The wave will lift float body and float body will pull the underwater glider through the cable, when the wave crest arrives. Therefore, wave glider will move up and simultaneously the wing plates will rotate downward

under the hydrodynamic force. Then, the underwater glider body will move downward because of its own gravity and meanwhile the wing plates will rotate upward under hydrodynamic force, when the wave trough arrives. As a result, it can be seen that the combined action of hydrodynamic force will produce a forward driving force in horizontal direction whether wave glider rises or falls, where the generation process of driving force is similar with underwater glider above.

The application of Wave Glider has achieved a great success in the PacX game from California to Australia, and set a new world record for the longest distance traveled by an autonomous vehicle (12,872 km), which attracts the attention of experts around the world (Villareal and Wilson 2014). By equipping different sensors on wave glider, a great many research work has been carried out in the ocean biological monitoring (Wiggins and Manley 2010; Meyer-Gutbrod et al. 2015; Manley and Hine 2016), water measurement (Van Lancker and Baeye 2015; Amiruddin 2016; Morales Maqueda et al. 2016), marine ecological environment research (Willcox et al. 2009; Frolov et al. 2011), marine meteorology (Lenain and Melville 2014; Mitarai and McWilliams 2016), etc. And many research institutes have made great achievements in the research of wave glider from different perspectives, such as Newcastle University (Morales Maqueda et al. 2016), University of Hawaii (Kraus and Bingham 2011; Foster et al. 2020), Ocean University of China (Sun et al. 2020; Wang et al. 2020a, b, c), Shenyang Institute of Automation, Chinese Academy of Sciences (Tian et al. 2014a, b; Tian et al. 2015), the National Ocean Technology Center (Qi et al. 2020a, b; Qi et al. 2020a, b), Harbin Engineering University (Wang et al. 2019; Yiming et al. 2021), Shanghai Jiao Tong University (Wang et al. 2020a, b, c; Wang et al. 2020a, b, c), etc.

3.3 Multifunction hybrid glider

Due to their excellent endurance, underwater glider and wave glider have been one of the most important AOOPs in ocean observation. However, the disadvantages are obvious: the underwater glider can only be used to collect the data in the ocean vertical profile, with low carrying capacity and poor ability to overcome strong current; simultaneously the wave glider can only glide on the ocean surface, and prone to be twined due to its complicated structure. In addition, the wave glider has weak maneuverability, with turning radius about 50 m on the ocean surface (Manley and Willcox 2010a, 2010b). Based on the deficiencies above, multifunctional hybrid glider (MHG), as a new type of AOOPs, is put forward, although it is still in the conceptual design or testing stage.

Caiti et al., from University of Pisa in Italy, presented a hybrid glider, called Underwater Wave Glider (UWG), by integrating the concept of underwater glider and wave

glider, to autonomously accomplish both surface and underwater missions, with an ideally unlimited endurance. UWG can realize two gliding modes by changing its shape: Wave Glider Mode (gliding on the ocean surface) and AUV/Glider Mode (gliding under the water) (Caiti et al. 2011). In addition, Caiti has established the vehicle dynamic model of UWG by a non-standard Lagrangian approach and given some simulations results. Another multifunctional hybrid glider is a robotic buoy system, mainly used for the fixed point ocean observation, designed by Joe et al., from South Korea Pohang University of Science and Technology (Joe et al. 2014). On the basis of wave glider, this robotic buoy system has snorkeling function by adjusting its buoyancy through two water pumps and can convert wave energy into electrical energy.

4 Recent advances in gliding robots

4.1 Deep sea underwater glider

With the development of underwater glider's technology and increasing demand for the deep-sea environment exploration, deep-sea glider has been put on the agenda, and has become the a hot spot around the world. University of Washington has developed a long range and deep-sea underwater glider, "Deepglider", with length 1.8 m, weight 62 kg, diving depth 6000 m, cruising range 10,000 km and continuous working time 18 months. Deepglider has successfully dived to 5920 m in the Atlantic sea trials (Osse and Eriksen 2007).

Deep sea glider "sea-wing 7000", developed by Shenyang Institute of Automation, the Chinese Academy of Sciences (SIACAS), has been successful in achieving the dive depth of 6329 m in Feb 2017 (Yu et al. 2017). Subsequently, "Petrel-X" underwater glider, developed by Tianjin University, has set a new world record for diving 8213 m in Mariana trench in Apr 2018, refreshing the underwater glider maximum dive depth (Li et al. 2019). The main parameters of the deep-sea glider described above are shown in Table 4.

4.2 Hybrid-driven underwater glider

Considering the underwater glider's single motion mode and its poor ability to resist current, some researchers tried to combines the advantage of conventional buoyancy-driven underwater glider with the propeller-driven AUV, and put forward the concept of Hybrid-driven underwater glider (HDUG) to realize a relatively higher endurance and a better capability to overcome strong current. The main parameters of some typical hybrid-drive underwater gliders are shown in Table 5. HDUG can operate in AUV mode or glider mode if necessary, which greatly improve its application prospect in ocean observation.

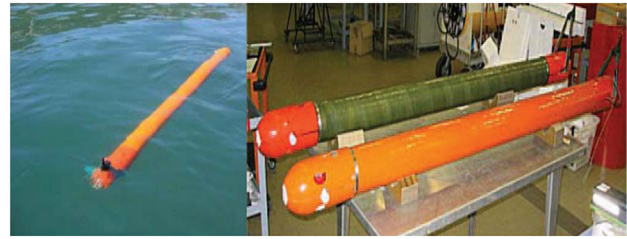
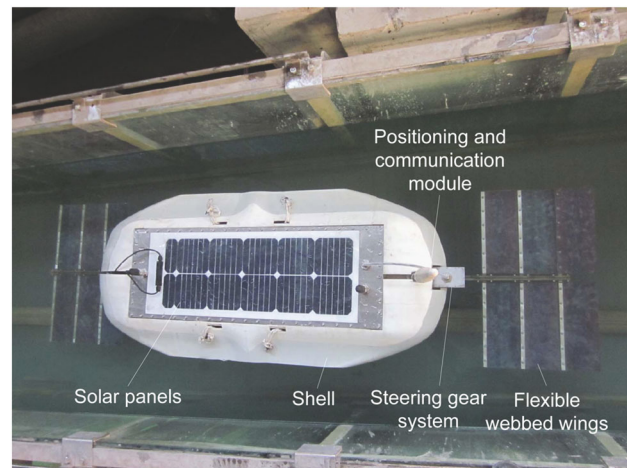
Table 4 Main parameters of deep-sea underwater glider

Deep sea underwater glider	Deepglider (Osse and Eriksen 2007)	Sea-wing 7000 (Yu et al. 2017)	Petrel-X (Li et al. 2019)
Length (m)	1.8	3.3	4
Diameter (m)	0.3	0.3	0.63
Net weight (Kg)	62	140	400
Depth capacity (m)	6000	6329	8213
Endurance	1 year, thousands km	2000kms	30 days, thousands km

Table 5 Main parameters of representative hybrid-driven underwater glider

Hybrid-driven underwater glider	Folaga (Alvarez et al. 2009; Caffaz et al. 2010)	SeaExplorer (Claustre et al. 2014)	Petrel-II (Liu et al. 2017)
Length (m)	2	2	2.17
Diameter (m)	0.14	0.25	0.22
Net weight (Kg)	30	59	69
Depth capacity (m)	50	700	1500
Average velocity (m/s)	1	1	1.5
Carrying capacity (Kg)	8	8	5
Motion mode	Hybrid glider/AUV	Hybrid glider/AUV	Hybrid glider/AUV

In 2010, Claus et al., from Memorial University of Newfoundland, have proposed a foldable propeller to reduce the impact of drag of the propellers and improve the horizontal flight performance, where the foldable propeller can be opened and folded according to its operating conditions (Claus et al. 2010). By introducing the pump-ejecting propellers, Integrated Systems for the Marine Environment (ISME), together with GraalTech (a spin-off company of the University of Genova), NATO Undersea Research Center (NURC) has designed a low-cost, small-weight HDUG Folaga (Alvarez et al. 2009; Caffaz et al. 2010), as shown in Fig. 7. Universiti Tun Hussein Onn Malaysia has developed a HDUG with propeller in the tail, independent tail wings and rudder, to increase its maneuverability (Isa et al. 2014; Isa and Arshad 2015). ACSA, a French company, has teamed up with a number of oceanographic institutes to develop HDUG, called SeaExplorer, which does not have wings or

**Fig. 7** The hybrid-driven underwater glider Folaga (Todd 2017)**Fig. 8** Prototype of multifunctional hybrid glider (MHG) in wave flume (Tian et al. 2016)

external moving parts aiding launch and recovery operations to reduce the risk of entanglement. Its modular design allows it to be quickly and conveniently replaced for different tasks or missions. In 2013, the SeaExplorer completed a two-month mission, which broke two world records for endurance for multisensor Unmanned Underwater Vehicle (UUVs) powered by rechargeable batteries. This fully verified the reliability and stability of the system, and it has been commercialized (Claustre et al. 2014). In addition, Shenyang Institute of Automation Chinese Academy of Sciences (SIA-CAS) (Chen et al. 2016), and Tianjin University (Wang et al. 2011) also carried out the study on related technology of HDUG.

4.3 Multifunctional hybrid glider with flexible wings

As a new type of platform, Multifunctional hybrid glider (MHG) with flexible wings can glide on the ocean surface or in the vertical profile, according to different observation missions. By introducing the flexible wings, Tian et al. put forward an scheme of MHG (Tian et al. 2016), as shown in Fig. 8. The driving force is generated by the elastic deformation of flexible wings under hydrodynamics.

Under the excitation of wave force, MHG has heave, pitch and roll motion on the ocean surface. There is a two-way fluid–structure coupling between the flexible fins and the water body. As a result, the combined action of fluid–structure coupling will produce a forward driving force in horizontal direction, where movement principle of MHG with flexible wings is very similar with wave glider, as shown in Fig. 9. Compared with wave glide, MHG with flexible wings has significant advantages as below. Firstly, MHG has more maneuverability because of its monomer structure, while steering for wave glider requires a complex process due to its multi-body structure, where torque of the steering gear in MHG is more easily applied to the whole vehicle. Moreover, MHG has higher energy absorption and conversion efficiency. MHG can make use its various motion (heave, pitch and roll) on water surface to generate driving force, while only the heave of the float body of Wave Glider contributes to its driving force. Finally, MHG has more functions, achieving surface and underwater movement according to the need, while Wave Glider has only surface gliding motion.

5 Prospectives

As is represented in Sects. 2 and 3, gliding robots have developed rapidly around the world and many excellent achievements have been made in recent years. With the introduction of more new technologies, it is certain that the gliding robots will have a brighter future and more applications in ocean observation.

5.1 Application of marine renewable energy

The marine renewable energy, is abundant, clean and pollution-free, with a great variety (such as solar energy, wave energy, tidal energy, salinity energy and thermal energy etc.). It is worth mentioning that this provides an important solution to solve the energy bottleneck for the endurance of gliding robots. At present, the solar energy, thermal energy

and wave energy have been successfully applied in the gliding robots. It is believed that there will be more technology and methods related to the application of marine renewable energy in gliding robots in the future, and this will become an important research topic.

5.2 Improvement of sensors carrying capability

The extensive application of gliding robots is largely dependent on their carrying sensors. However, many sensors on the gliding robots are restricted by their volume, weight, and energy consumption, due to gliding robots' finite carrying capacity (such as underwater glider with general carrying capacity only several kilograms), which impose restrictions on the further application of gliding robots in the ocean operations. Therefore, it is significant to promote the carrying capacity of the gliding robots to improve their function and expand their application in ocean observation.

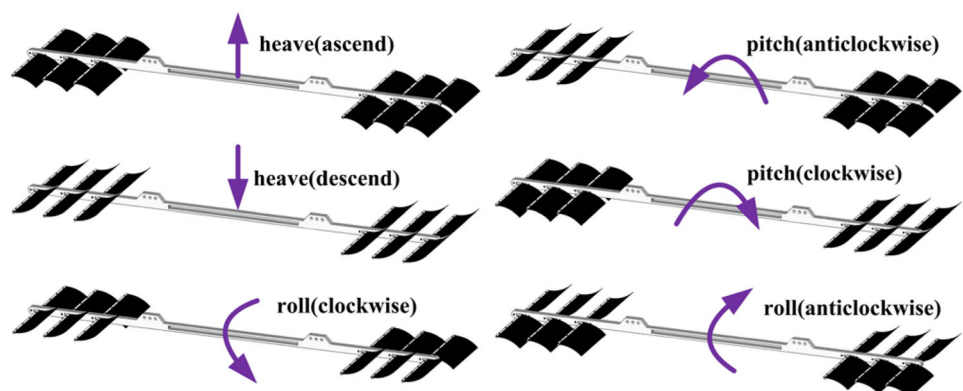
5.3 Intelligent level

With the development of big data analysis, image recognition, artificial intelligence etc., the intelligent level of gliding robots will be gradually improved. Through the real-time intelligent perception and deep learning of the marine environment, gliding robots can obtain the information and data of their own parameters and the surrounding marine environment, so as to realize their intelligent operation and autonomous decision-making ability in the complex marine environment. The intelligence of gliding robots is of great help to improve the efficiency of ocean observation, the emergency treatment of ocean emergencies and the realization of safe operation.

5.4 High stability and reliability

The stable and reliable performance of gliding robots is closely related to their structural design, electronic system, control algorithm and communication etc., which provides

Fig. 9 The deformation of flexible webbed wings when MHG heaves, pitches and rolls (Tian et al. 2016)



the basic guarantee for their long-term and large-range application in ocean observation. It is often fatal when the gliding robots malfunction, resulting in the failure of ocean-observation missions and even the risk of robot losing contact and loss, especially in the harsh sea conditions. It will improve the stability and reliability of gliding robots to adopt existing mature technology, introduce latest research achievements and multi-system optimization and integration etc.

5.5 Functional diversity

With the development of marine scientific research, gliding robots should be required to realize different observation strategies, according to different requirements of ocean operations. Not only the endurance needs to be strong, but their function should be diversified as well. For example, Multifunctional hybrid glider can glide on the ocean surface and in the vertical profile, which can complete the large range, multitasking, long-term and three-dimensional ocean observation in the future comprehensive and complex ocean environment.

6 Conclusion

As the activity processes for humans continue to progress in exploitation and exploration of the ocean, gliding robots, as important autonomous ocean-observation platforms, plays an important role in this event with their excellent endurance and satisfactory performance. This paper conducted a review of the current gliding robot applied in ocean observation and analyzed the research progress and development trend of related technology in gliding robots, which will provide a reference for AOOPs construction and application selection in ocean observation. Believe that they will make a significant impact on the ocean research with further technical difficulties conquered.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

- Alvarez A, Caffaz A, Caiti A, Casalino G, Gualdesi L, Turetta A, Viviani R (2009) Fòlaga: A low-cost autonomous underwater vehicle combining glider and AUV capabilities. *Ocean Eng* 36:24–38
- Amiruddin SM (2016) Real-time Web GIS to monitor marine water quality using wave glider. In: 8th IGRSM international conference and exhibition on geospatial and remote sensing, IGRSM 2016, April 13, 2016–April 14, 2016. Antaragrafik Systems Sdn. Bhd, Kuala Lumpur
- Arima M, Tonai H (2012) Feasibility study of an ocean-going solar-powered underwater glider. In: 22nd International offshore and polar engineering conference, ISOPE-2012, June 17, 2012–June 22, 2012, Rhodes, Greece, pp 532–537
- Arima M, Okashima T, Yamada T (2011) Development of a solar-powered underwater glider. In: 2011 IEEE symposium on underwater technology, UT’11 and workshop on scientific use of submarine cables and related technologies, SSC’11, April 5, 2011–April 8, 2011, Tokyo, Japan
- Arima M, Tonai H, Yoshida K (2014a) Development of an ocean-going solar-powered underwater glider. In: 24th International ocean and polar engineering conference, ISOPE 2014a Busan, June 15, 2014a–June 20, 2014, Busan, Republic of Korea, pp 444–448
- Arima M, Yoshida K, Tonai H (2014b) Development of a coral monitoring system for the use of underwater vehicle. In: OCEANS 2014b, Taipei, pp 1–6
- Caffaz A, Caiti A, Casalino G, Turetta A (2010) The hybrid glider/AUV folaga: field experience at the GLINT’08 experiment. *IEEE Robot Autom Mag* 17:31–44
- Cai L (2016) Performance evaluation and parametric optimum design of an updated ocean thermal energy conversion system. *Ocean Eng* 117:254–258
- Caiti A, Calabro V, Grammatico S, Munafo A, Stifani M (2011) Lagrangian modeling of the Underwater Wave Glider. In: Proceedings of MTS/IEEE oceans 2011, June 06–June 09, 2011, Santander, Spain, pp 1–6
- Cauchy P, Heywood KJ, Merchant ND, Queste BY, Testor P (2018) Wind speed measured from underwater gliders using passive acoustics. *J Atmos Ocean Tech* 35:2305–2321
- Cazau D, Bonnel J, Baumgartner M (2019) Wind speed estimation using acoustic underwater glider in a near-shore marine environment. *IEEE Trans Geosci Remote Sens* 57:2097–2106
- Chen Q (2014) Unmanned underwater vehicle, 1st edn. National Defense Industry Press, London
- Chen Z, Yu J, Zhang A, Zhang F (2016) Design and analysis of folding propulsion mechanism for hybrid-driven underwater gliders. *Ocean Eng* 119:125–134
- Claus B, Bachmayer R, Williams CD (2010) Development of an auxiliary propulsion module for an autonomous underwater glider. *Proc Inst Mech Eng Part m J Eng Maritime Environ* 224:255–266
- Claustre H, Beguery L, Patrice PLA (2014) SeaExplorer glider breaks two world records multisensor UUV achieves global milestones for endurance, distance. *Sea Technol* 55:19–22
- Eriksen CC, Osse TJ, Light RD, Wen T, Lehman TW, Sabin PL, Ballard JW, Chiodi AM (2001) Seaglider: a long-range autonomous underwater vehicle for oceanographic research. *IEEE J Ocean Eng* 26:424–436
- Foster JH, Eriksen TL, Bingham B (2020) Wave glider-enhanced vertical seafloor geodesy. *J Atmos Ocean Tech* 37:417–427
- Frolov S, Bellingham J, Anderson W, Hine G (2011) Wave Glider—a platform for persistent monitoring of algal blooms. In: Proceedings of MTS/IEEE oceans 2011, Kona, Hawaii, pp 1–5
- Georgiades C, Nahon M, Buehler M (2009) Simulation of an underwater hexapod robot. *Ocean Eng* 36:39–47

- Hine R, Willcox S, Hine G, Richardson T (2009) In: Proceedings of MTS/IEEE oceans 2009, Biloxi, pp 1–6
<http://liquidr.com/>
- Isa K, Arshad MR (2015) Development of a hybrid-driven autonomous underwater glider with a biologically inspired motion control system. In: 2015 10th Asian Control Conference (ASCC), May 3–June 03, 2015, Kota Kinabalu, Malaysia, pp 1–6
- Isa K, Arshad MR, Ishak S (2014) A hybrid-driven underwater glider model, hydrodynamics estimation, and an analysis of the motion control. *Ocean Eng* 81:111–129
- Joe H, Lee JS, Kim M, Wi S-M, Kwon H-S, Yu S-C (2014) Development of oceanic energy harvesting robotic buoy for persistent operation. In: 24th International ocean and polar engineering conference, ISOPE 2014 Busan, June 15, 2014–June 20, 2014, Busan, Republic of Korea, pp 405–409
- Kraus N, Bingham B (2011) Estimation of wave glider dynamics for precise positioning. In: Proceedings of MTS/IEEE oceans 2011, September 19–September 22, 2011, Waikoloa, HI, USA, pp 1–9
- Lenain L, Melville WK (2014) Autonomous surface vehicle measurements of the ocean's response to tropical cyclone Freda. *J Atmos Ocean Tech* 31:2169–2190
- Letcher TM (2008) *Future energy: improved, sustainable and clean options for our planet*. Elsevier, Oxford
- Li H, Wang Y, Wang S (2019) Underwater glider Petrel-X glider rated to 10,000 M for hadal zone research. *Sea Technol* 60:18–22
- Liu F, Wang Y-H, Wu Z-L, Wang S-X (2017) Motion analysis and trials of the deep sea hybrid underwater glider Petrel-II. *China Ocean Eng* 31:55–62
- Liu Z, Chen X, Yu J, Xu D, Sun C (2019) Kuroshio intrusion into the South China Sea with an anticyclonic eddy: evidence from underwater glider observation. *J Oceanol Limnol* 37:1469–1480
- Manley JE, Hine G (2016) Unmanned surface vessels (USVs) as tow platforms: wave glider experience and results. In: Proceedings of MTS/IEEE oceans 2016, Monterey, CA, United states
- Manley J, Willcox S (2010a) The Wave Glider: a persistent platform for ocean science. In: OCEANS 2010a, Sydney, pp 1–5
- Manley J, Willcox S (2010b) The Wave Glider: a new concept for deploying ocean instrumentation. *IEEE Instr Meas Mag* 13:8–13
- Morales Maqueda MA, Penna NT, Williams SDP, Foden PR, Martin I, Pugh J (2016) Water surface height determination with a GPS wave glider: a demonstration in Loch Ness, Scotland. *J Atmos Ocean Tech* 33:1159–1168
- Meyer-Gutbrod EL, Greene CH, McGarry LP (2015) Wave glider technology for fisheries research new integrated instrumentation expands the fisheries acoustics toolbox. *Sea Technol* 56:15–19
- Mitarai S, McWilliams JC (2016) Wave glider observations of surface winds and currents in the core of Typhoon Danas. *Geophys Res Lett* 43:11312–11319
- Osse TJ, Eriksen CC (2007) The Deepglider: a full ocean depth glider for oceanographic research. In: Proceedings of MTS/IEEE oceans 2007, Vancouver, BC, Canada
- Qi Z, Zhai J, Qin Y (2020a) Dynamic analysis and adaptive obstacle avoidance algorithm of wave glider based on fuzzy control. *J Intell Fuzzy Syst* 38:1349–1358
- Qi Z, Zou B, Lu H, Shi J, Li G, Qin Y, Zhai J (2020b) Numerical investigation of the semi-active flapping foil of the wave glider. *J Mar Sci Eng* 8:303
- Qiu C, Mao H, Wang Y, Yu J, Su D, Lian S (2019) An irregularly shaped warm eddy observed by Chinese underwater gliders. *J Oceanogr* 75:139–148
- Roberts G, Sutton R (2006) *Advances in unmanned marine vehicles*. Institution of Engineering and Technology, London
- Rudnick DL, Davis RE, Eriksen CC, Fratantoni DM, Perry MJ (2004) Underwater gliders for ocean research. *Mar Technol Soc J* 38:73–84
- Rudnick DL, Zaba KD, Todd RE, Davis RE (2017) A climatology of the California current system from a network of underwater gliders. *Prog Oceanogr* 154:64–106
- Sherman J, Davis R, Owens WB, Valdes J (2001) The autonomous underwater glider “Spray.” *IEEE J Ocean Eng* 26:437–446
- Stommel H (1989) The Slocum mission. *Oceanography* 2:22–25
- Sun X, Zhou Y, Sang H, Yu P, Zhang S (2020) Adaptive path following control for wave gliders in time-varying environment. *Ocean Eng* 218:1–14
- Tian B, Yu J (2019) Current status and prospects of marine renewable energy applied in ocean robots. *Int J Energy Res* 43:2016–2031
- Tian B, Yu J, Zhang A, Jin W, Zhao W, Chen Z (2014a) Analysis on movement efficiency for wave driven unmanned surface vehicle. *Robot* 36(43–48):68
- Tian B, Yu J, Zhang A, Zhang F, Chen Z, Sun K (2014b) In: Proceedings of MTS/IEEE oceans'14, Taipei
- Tian B, Yu J, Zhang A (2015) In: 2015 IEEE international conference on cyber technology in automation, control and intelligent systems, IEEE-CYBER 2015. IEEE, Shenyang, pp 1253–1258
- Tian B, Zhou W, Li L, Yao Z (2016) Research on realization mechanisms of multifunctional hybrid glider. In: Proceedings of MTS/IEEE oceans 2016, Shanghai, China, pp 1–6
- Todd RE (2017) High-frequency internal waves and thick bottom mixed layers observed by gliders in the Gulf Stream. *Geophys Res Lett* 44:6316–6325
- Van Lancker V, Baeye M (2015) Wave glider monitoring of sediment transport and dredge plumes in a shallow marine sandbank environment. *PLoS ONE* 10:e0128948
- Villareal TA, Wilson C (2014) A comparison of the Pac-X trans-Pacific wave glider data and satellite data (MODIS, Aquarius, TRMM and VIIRS). *PLoS ONE* 9:1–18
- Vincent AG, Pascal RW, Beaton AD, Walk J, Hopkins JE, Woodward EMS, Mowlem M, Lohan MC (2018) Nitrate drawdown during a shelf sea spring bloom revealed using a novel microfluidic in situ chemical sensor deployed within an autonomous underwater glider. *Mar Chem* 205:29–36
- Wang S, Sun X, Wang Y, Wu J, Wang X (2011) Dynamic modeling and motion simulation for a winged hybrid-driven underwater glider. *China Ocean Eng* 25:97–112
- Wang L, Li Y, Liao Y, Pan K, Zhang W (2019) Dynamics modeling of an unmanned wave glider with flexible umbilical. *Ocean Eng* 180:267–278
- Wang D, Wang P, Zhang X, Guo X, Shu Y, Tian X (2020a) An obstacle avoidance strategy for the wave glider based on the improved artificial potential field and collision prediction model. *Ocean Eng* 206:1–12
- Wang P, Wang D, Zhang X, Li X, Peng T, Lu H, Tian X (2020b) Numerical and experimental study on the maneuverability of an active propeller control based wave glider. *Appl Ocean Res* 104:102369
- Wang X, Chang Z, Zheng Z, Zhang J, Feng Z, Lu G (2020c) Analysis and selection of deployment methods for a wave glider system. *J Mar Sci Eng* 8:1–12
- Webb DC, Simonetti PJ, Jones CP (2001) SLOCUM: an underwater glider propelled by environmental energy. *IEEE J Ocean Eng* 26:447–452
- Wiggins S, Manley J, Brager E, Woolhiser B (2010) Monitoring marine mammal acoustics using Wave Glider. In: Proceedings of MTS/IEEE oceans 2010, September 20–September 23, 2010, Seattle, WA, USA, pp 1–4
- Willcox S, Meinig C, Sabine CL, Lawrence-Slavas N, Richardson T, Hine R, Manley J (2009) An autonomous mobile platform for underway surface carbon measurements in open-ocean and coastal waters. In: Proceedings of MTS/IEEE Oceans 2009, Biloxi, MS
- Wood SL, Mierzwa CE (2013) State of technology in autonomous underwater gliders. *Mar Technol Soc J* 47:84–96

- Yiming L, Ye L, Shuo P (2021) Variable-structure filtering method for an unmanned wave glider. *Appl Ocean Res* 107:1–10
- Yu J, Jin W, Tan Z, Huang Y, Luo Y, Wang X (2017) Development and experiments of the Sea-Wing7000 underwater glider. In: *Proceedings of MTS/IEEE oceans 2017*, September 18–September 21, 2017, Anchorage, AK, United states, pp 1–7
- Yu J, Zhang F, Zhang A, Jin W, Tian Y (2013) Motion parameter optimization and sensor scheduling for the sea-wing underwater glider. *IEEE J Ocean Eng* 38:243–254
- Zhang S, Yu J, Zhang A, Zhang F (2013) Spiraling motion of underwater gliders: modeling, analysis, and experimental results. *Ocean Eng* 60:1–13
- Zhang B, Song B, Mao Z, Li B (2018) Layout optimization of landing gears for an underwater glider based on particle swarm algorithm. *Appl Ocean Res* 70:22–31
- Zhou M, Bachmayer R, Deyoung B (2019) Mapping the underside of an iceberg with a modified underwater glider. *J Field Robot* 36:1102–1117

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