Current status and prospects of marine renewable energy applied in ocean robots

Baoqiang Tian$^{1,2,3}$ | Jiancheng Yu$^3$

$^1$State Key Laboratory of Mechanical Transmissions, Chongqing University, Chongqing, China
$^2$Marine Equipment and Technology Institute, Jiangsu University of Science and Technology, Zhenjiang, China
$^3$State Key Laboratory of Robotics, Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang, China

Summary

The power supply for ocean robots has always been an important issue since it has a fatal influence on the endurance of these vehicles. However, the marine renewable energy (MRE) has huge potential and can provide the possibility to solve this problem between essential endurance and finite energy in ocean robots. This paper starts with brief introduction of marine energy resource and ocean robots and presents significance of improving ocean robots' endurance, through comparison of their performance characteristics. MRE applied in ocean robots developed or under development, including energy conversion and driving principle, is reviewed, such as solar, wind, tides, waves, thermal energy, etc. Many challenges and difficulties are also discussed in energy exploitation and utilization related to ocean robots. Finally, the prospect for the future development of related technologies is proposed in this paper.

KEYWORDS

endurance, marine renewable energy, ocean robots, power supply, review

1 | INTRODUCTION

The world economy's development may benefit from the wide application of terrestrial fossil energy, such as oil, natural gas, coal, and so on. However, with the over-exploitation of the energy, this resource carrier of the economy is facing an increasingly exhausted crisis. Meanwhile, the irrational use of fossil energy has caused great damage to the environment and derived global climate and environmental problems.$^1$ The contradiction among the economy, environment, and energy has prompted scientific researchers around the world to turn their attention to the ocean with the rich resources. It is of great significance to rationally develop marine resources in alleviating energy crisis, reducing environmental pollution, and promoting economic development. It is estimated that the reserves of marine energy resource are about tens to hundreds of times the earth’s. More importantly, these are all green, clean, and inexhaustible renewable energy.$^2$

Ocean robots are generally considered to be unmanned vehicles with certain intelligence, including unmanned surface vehicle (USV) and unmanned underwater vehicle (UUV). The USV, also called autonomous
surface vehicle (ASV), generally moves on the surface of the water. The UUV can be applied to carry out underwater operation, and it is well known to consist of two main categories: remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs). The difference between AUVs and ROVs is that AUV can perform a task without human supervision, such as sensing and automatic decision making, while ROV fulfills a mission by instructions from an operator via a tethered cable (providing power, data links, and control). Furthermore, some new concept ocean robots began to emerge, such as buoyancy-driven underwater glider (UG), wave glider, multifunction hybrid glider (MHG), etc.

The power supply for ocean robots has always been an important issue since it has a fatal influence on the endurance of these vehicles. According to the existing literature data, the energy sources of power supply systems for ocean robots can generally be divided into two categories: batteries and marine renewable energy (MRE). Batteries have been regarded as primary power sources for most ocean robots (such as alkaline battery, lithium battery, fuel cells, etc), because they have the small size and high energy density, and directly provide electrical energy without absorption and conversion. However, the fatal flaw of batteries is that they have limited energy, not enough to support ocean robots to complete large-range and long-term marine operations. The contradiction between their strong endurance and finite energy constitutes the bottleneck for their further application in ocean operations. On the other hand, combined with the working circumstances of ocean robots, it will be more effective to equip the MRE on ocean robots, which will solve this problem between essential endurance and finite energy in ocean robots. Meanwhile, MRE has advantages of green, clean, and inexhaustibility, where these features make MRE very suitable for use as an energy sources for ocean robots. However, the disadvantages of MRE are also obvious, such as vulnerable to environmental influences and constraints, low energy density, etc. For meeting the different needs of marine applications, various types of ocean robots powered by MRE began to emerge in large numbers, and their endurance has been greatly improved. The different performance characteristics of some typical ocean robots are summarized in Table 1, such as USV, AUV, ROV, UG, and wave glider.

It can be seen from Table 1 that wave glider has tens to hundreds times higher than other ocean robots in endurance (mainly of working time and working range), which is mainly because of the application of MRE. The ocean robots, such as USV, AUV, etc, commonly use the battery as their power supply, so their endurance is mainly restricted by the battery capacity. The continuous power required by ROV is provided by the marine ship over the tether between them, so ROV working range is limited largely by tether length, and its cost is very high because of the logistic support of the marine ship. Simultaneously, because of new driving mode of buoyancy change, UG can realize zigzag movement in the vertical profile of ocean. However, wave glider is a new-type USV, equipping with wave energy and solar energy, which has already become an important ocean observation platform, for its strong endurance, low cost, active control, etc.

Ocean robots have been regarded as one of the most important tools for understanding and exploring ocean, especially in those dangerous and inaccessible places (for instance, harsh or underwater high-pressure environment). At present, ocean robots have been successfully applied in many marine areas, such as submarine resource exploitation (manganese nodule, hydrothermal deposits, etc), hydrographic survey, pipeline inspection, ocean observation, military applications (mine clearance, anti-submarine warfare, etc), and so on. This paper summarizes the application of MRE in ocean robots and presents the important significance of improving ocean robots’ endurance by introducing MRE, which will provide a reference for MRE development and ocean robot construction in future research related to marine engineering technology.

### TABLE 1 Summary table of performance characteristics of different ocean robots

| Ocean Robots | Working Time | Working Range | Measured Water |
|--------------|--------------|---------------|----------------|
| AUV          | Hours to days| Tens to hundreds kilometers | Deep water |
| ROV          | Days to months | Tens to hundreds kilometers | Deep water |
| USV          | Days to months | Hundreds to thousands kilometers | Surface water |
| UG           | Weeks to months | Hundreds to thousands kilometers | Deep water |
| Wave glider  | Months to years | Thousands to tens of thousands kilometers | Surface water |

Abbreviations: AUV, autonomous underwater vehicle; ROV, remotely operated vehicle; UG, underwater glider; USV, unmanned surface vehicle.
Solar energy generally is regarded as the radiant energy of sunlight, which is taken as the inexhaustible, renewable, green, and clean energy. In addition, almost all the MRE sources are considered to originate from the solar energy, such as wind energy, wave energy, etc. Figure 1 shows that solar radiation is closely related to the terrestrial latitude and the ocean areas with the most intense solar radiation are between 30° north and 30° south latitudes.

The solar energy can be transformed into electric energy through solar photovoltaic system and store the electric energy in the battery (storage battery, lithium battery, etc) to ensure that ocean robots have strong endurance to successfully complete the large-range and long-term ocean missions. Many researchers have done many trial and research work related with the solar energy’s application in ocean robots, such as AUV, USV (or ASV), UG, etc, as illustrated in Figure 2. Because of the rapidly decreasing of solar energy under water, it is necessary for these ocean robots to absorb the solar energy on the ocean surface.

### 2.1.1 Solar-powered AUV

Institute for Marine Technology Problems, Russian Academy of Sciences, cooperating with the Autonomous Undersea Systems Institute (AUSI), had carried out the research effort in solar-powered AUV since 1997 and developed engineering prototype solar-powered AUV (SAUV) I, with 90-kg weight, 1.7-m length, and 0.7 m wide. Its power system consists of two Solarex (MSX30L) 30-W solar panels and four batteries (32 NiCd cells). In order to verify its endurance measurements in the ocean, SAUV I has undergone sea testing near...
Vladivostok for 22 days.\textsuperscript{31} On the basis of the successful test of SAUV I, AUSI, cooperating with Technology Systems Inc and Falmouth Scientific Inc, had developed the SAUV II, with 200-kg weight, 2.3 m length, and 1.1 m wide, max operating depth of 500 m, speed of 0.75 to 3 knots,\textsuperscript{25,32,33} as shown in Figure 2A. Compared with SAUV I, energy system of SAUV II has been optimized and equipped with BP585 solar panel (maximum power of 85 W), Li-ion battery (2 kW-h), and its endurance has been greatly improved.\textsuperscript{34} On the basis of SAUV II prototype, many field experiments have been undertook in Lake George (in June and October, respectively) and Greenwich Bay (in August) in 2004, which focus on the communication and cooperation among multiple AUVs.\textsuperscript{32}

### 2.1.2 Solar-powered USV

Because of USVs only sailing on the water surface, it is convenient to absorb the solar energy and achieve the conversion of solar energy to electric energy. In order to provide the platform for the ocean environment and marine mammals monitoring, Osaka Prefecture University has developed a solar-powered ASV (SASV), with 81.2-kg weight, 2.87-m length, 0.79 m wide, max speed of 2 knots. Its solar power system includes two 100-W solar panels, a controller for charge and discharge and a 12-V battery (115 Ah). The SASV’s maneuverability, wireless communication, and photovoltaic power system have also passed the test in swimming pool,\textsuperscript{26} as shown in Figure 2B. Emergent Space Technologies, Inc has developed an ASV powered by solar for providing a low-cost, reconfigurable, and long-duration platform applied in oceanographic and atmospheric scientific research, such as phytoplankton productivity and carbon dioxide-air sea flux, which has about 5.5-m length, 1.5-m width, 1.8-m height, and 1360-kg weight.\textsuperscript{27} as shown in Figure 2C. Unmanned Ocean Vehicles (UOV) Inc has developed USV powered by solar and wind energy, where solar cells, equipped on the rigid sails, generated electricity for consumption of onboard electronic devices. This prototype was designed ranging from 4.57 to 8.23 m in length.\textsuperscript{35} Besides, Villanova University has conducted research on hybrid power system of USV comprising a solar array, a fuel cell system, an ocean wave energy converter, etc. It will preferably meet the requirements for USV’s long-duration missions, by modeling and optimizing its hybrid power system.\textsuperscript{36}

### 2.1.3 Solar-powered UG

Arima et al from Osaka Prefecture University in Japan have made a lot of researches on related technology of solar-powered UG. In order to study the relationship between solar power supply system and laboratory environment, an experimental platform, SORA, has been established, with 3.48-kg weight, 0.7-m length, 0.73 m wide, and 0.205-m height, to demonstrate the possibility of solar energy application in the UG.\textsuperscript{37,38} Subsequently, this team has developed a solar-powered UG, Tonai60, to be applied to monitor shallow coral reefs, as shown in Figure 2D, with 92-kg weight, 1.65-m length, 1.03 m wide, height of 0.528 m. Tonai60 can dive to 60 m and was equipped with a network camera, a digital compass, and an environmental data logger, which can record the water depth, temperature, salinity, chlorophyll, turbidity, and other environmental data.\textsuperscript{28,39} Because of their unique driving principle and motion mode, the solar-powered UG has to adjust their attitude to the level state on the water surface to achieve charging the batteries.

### 2.2 Wind energy

As a conversion form of solar energy, wind energy is the kinetic energy of the streaming air, resulting from the pressure differential caused by unevenly heated land and sea from the sun radiation. The significant characteristic of wind power is its abundant reserves, nonpollution, and inexhaustibility, while it also has the disadvantages of low energy density, variability of its generation, direction, and speed in space and time.\textsuperscript{40} Figure 3 shows the global distribution of mean wind speed from satellite data. It can be found that regions with the highest wind speed are mainly located in the westerlies of the northern and southern hemispheres and value of wind speed decreases gradually to the lower latitude. Meanwhile, Indian Ocean and East China Sea also have higher wind speeds due to the monsoon.\textsuperscript{41}

The ocean contains abundant wind power, and it has been widely applied in wind-power generation. In addition, wind power can also be harnessed and converted for power supply of ocean vehicles, such as autonomous sailboat. Autonomous sailboat is a wind-powered USV and can realize the zigzag trajectory on the ocean surface. With the long-range endurance, it has the potential advantage of providing detailed data from targeted locations to support ocean research, such as marine environment and ecology, weather monitoring, surveillance platform for port observation,\textsuperscript{42} etc. Sails or wings, as the propulsion part of sailboats, can realize to transform the wind power into the driving force. When the angled lifting surface of sails (or wings) is exposed to the streaming air with a certain velocity, the aerodynamic forces acting on them can be denoted as lift force and drag force, where combined action of this two forces will produce a
driving force. These sailboats can move forward constantly on the ocean surface under the action of this driving force.

Many scholars around the world have carried out research on the relevant technology of sailboat and established various platforms to meet the requirements of many different marine applications, as shown in Figure 4. Erckens et al from Swiss Federal Institute of Technology have built the autonomous robotic sailboat AVALON to compete in the MICROTRANSAT Challenge and presented navigation software and to calculate the optimal path to reach the specified destination, which
has been tested in Swiss lakes and Atlantic Ocean and proved to control its sailing route, even under bad sea conditions.\(^{44}\) The Faculty of Engineering at the University of Porto (FEUP) has designed a robotic sailing vehicle (FASt), which can achieve the function of autonomous navigation.\(^{48-52}\) FAST’s performances (in upwind mode, downwind mode, station keeping, etc) are represented in many sea trials.\(^{52}\) Luiz Goncalves et al in Brazil have developed two prototypes of autonomous sailboat (N-Boat I and N-Boat II) and also studied the technology-related sailboat, including control strategies, hardware architecture, prototype design, etc.\(^{46,53-55}\) National Oceanic and Atmospheric Administration (NOAA), partnered with Saildrone Inc, has developed an USV, called Saildrone, for research in the arctic warming, marine animals, and ecosystem change. In 2015, Saildrones have successfully completed the atmospheric and oceanic measurement mission of Bering Sea for 97 days, and in 2016, Saildrones have been deployed in harsh Bering Sea to survey the fisheries, marine mammal, etc.\(^{47,56}\) The team from Florida Atlantic University has developed an ASV powered by wind and solar, WASP, to monitor the distribution of ocean conditions and meteorological for a long time. Additionally, a small folding propeller is mounted beneath the WASP for use under the situation with little wind.\(^{43,45}\)

### 2.3 Tidal current energy

Tidal current energy can be defined as the kinetic energy contained in the seawater with a certain horizontal velocity, caused by gravitational interaction among the earth, moon, and sun.\(^{57,58}\) It is different from tidal energy because of their energy storage form, where tidal current energy is kinetic energy in seawater with a certain velocity, while tidal energy is the potential energy of seawater because of sea level variation. Compared with other MRE sources, tidal current energy has great development prospect mainly because of its advantages of the high energy density and predictability.\(^{59-61}\)

Shi et al from Newcastle University have proposed a novel concept AUV powered by tidal current energy to enhance its endurance,\(^{62}\) as shown in Figure 5. This AUV consists of three subsystems to realize this function. The first subsystem mainly includes twin diffuser-augmented tidal turbines (DATTs), working as the power generator to charge the batteries of AUV. DATTs can incessantly convert tidal current energy to the electric power to supply the instruments carried on board or thrusters, where thin-wall diffusers are integrated to increase their energy capture capability. In order to achieve the most optimal energy-exchange efficiency, the turbines should be kept in the line with the direction of flow. The second subsystem includes two cross rudders, gyroscope, and ballast water tanks, to control the attitude and motion of AUV. The third subsystem is a mooring system for anchoring the device to the seabed, which will apply the AUV to adapt with the direction of flow and adjust the device submergence depth by the mooring chain. Then, its parameters and drag of diffuser are optimized to acquire a higher turbine-power coefficient, and its numerical optimization is validated through two sets of physical model. The reference of mooring system increases the complexity of the device and the dependence of AUV on the environment, which is not conducive for AUV to carry out autonomous operations in ocean.

### 2.4 Wave energy

Wave energy is generated by the wind frictional force on water surface, and the values of wave properties depend on the wind speed, direction, their duration, etc.\(^{53}\) Besides, wave energy is enormous, more persistent, and spatially concentrated than many other renewable resources. Meanwhile, it has a higher power energy density than wind and solar energy.\(^{64,65}\) As shown in Figure 6, the most abundant area of wave energy is mainly concentrated in the southern Indian Ocean, North Pacific, North Atlantic, etc, while areas near the equator have relatively lower wave energy.\(^{66}\)

These features facilitate the development of wave energy, and many research achievements on its exploitation have been flourishing over the past few decades, such as wave energy converter (WEC).\(^{67,68}\) The possibility of applying wave energy in ocean robots has inspired numerous researchers. Currently, the conversion and utilization of wave energy mainly include two branches: one
is to convert wave into electricity to supplement the power consumption of ocean robots, through certain methods and devices; the other is to turn the wave directly into the driving force to pull the robot to move forward by some mechanical devices.

2.4.1 Convert wave directly into driving force

Tokai University presented an autonomous boat powered by wave for ocean observations, with approximately 5.2-kg weight, 1.30-m length, 0.98-m breadth, and 0.7-m height, as shown in Figure 7. It can directly transform the wave energy into its driving force through double-fin wave devouring propulsion system (WDPS), where each fin was connected with a spring providing an adequate restoring moment and oscillating about a pivot axis under the wave action. Besides, two rudders, installed behind the hull and driven by two servo motors, realize the direction control of boat.

As another platform to convert wave energy directly into driving force, wave glider is a new concept USV, using wave energy to obtain driving force and converting solar energy to electric power to supply its electricity consumption. In 2005, the original concept of wave glider was firstly proposed by American Liquid Robotics Inc, with multibody structure.

Its movement principle of wave glider can be demonstrated in Figure 8. Under the effect of wave action and its own gravity, the float body will rise or fall on the ocean surface. When the float body rises, the UG body will move up under the pull of the float body through the cable, and the wings will rotate downward under the hydraulic resistance on their upper surface. When the float body falls, the UG body will sink because of its own gravity, and the wings rotate upward under the hydraulic resistance on their lower surface. Therefore,
the driving force will be generated because of the combined action of the hydrodynamic force of wings, where the driving force is always toward the front whether wave glider rises or falls. It is obvious that the UG body is its dynamic part and pulls the whole wave glider to move forward, independent of the wave direction. The rudder, equipped on the UG body, is used to steer the wave glider’s direction.72

It was a great success for wave glider in the PacX game (from California to Australia), which has created a new world record for the longest distance traveled by an autonomous vehicle (12,872 km) and attracted the attention of experts around the world.73 By equipping with different sensors on wave glider, considerable research work has been carried out in the ocean biological monitoring,74-76 water measurement,77-79 marine ecological environment research,80,81 marine meteorology,82,83 etc. At present, the wave glider has been commercialized to serve a variety of scientific research, based on its reliability performance.

On the basis of the study of UGs and wave gliders, Tian et al, from Jiangsu University of Science and Technology, put forward a scheme of multifunctional hybrid glider (MHG) by introducing the flexible webbed wings,84 as shown in Figure 9. MHG is powered by wave and solar energy and can glide on the ocean surface or in the vertical profile according to the different research demands, overcoming the single motion mode of UG or wave glider. It is obvious that MHG has great potential application prospects in the future three-dimensional ocean observation, for its versatility function.

The conversion from wave energy to driving force is realized by the elastic deformation of flexible webbed wings under hydrodynamic force, compared with the rigid wing plate rotating around the shaft in wave glider. Its motion principle and generation process of driving force are very similar with wave glider, while the obvious difference is that the motion of the shell can be transmitted to webbed wings in real time because wings are fixed on the shell. When MHG glides on ocean surface or in the vertical profile, its generation process of driving force is similar with UG and wave glider above through the flexible webbed wings. Besides, the deformation of wings has the same motion state, when MHG has heave motion, while the deformation of fore-and-aft and bilateral wings has the opposite motion state, when MHG has pitch and roll motion, respectively. The driving force is always generated, regardless of the movement state of MHG, while for wave glider, only the heave motion of float body can generate the driving force. Therefore, the application of flexible wings in MHG will substantially enhance the conversion and utilization efficiency of wave energy, compared with wave glider.

2.4.2 | Convert wave into electric energy

Townsend et al, from University of Southampton, put forward a novel gyroscopic wave-energy scavenging system for AUV, capable of generating electricity and recharging its battery from wave energy. This system utilizes the gyroscopic response of a gimballed flywheel to realize the energy transformation from wave to electricity, based on the control moment gyroscope principles, where the rotational motions of the flywheel in AUV are excited by wave action.85,86 Admittedly, there are several potential advantages in this system, including not susceptible to bio-fouling and not adding any hydrodynamic drag because it is housed in AUV, enabling AUV to be remotely recharged to extend its missions scope, reducing AUV battery requirements (such as size and weight) and costs of its deployment,87 etc.

In addition, Nicholas Townsend has set up an experimental platform, as illustrated in Figure 10, with flywheel diameter of 0.1 m, spin rate of 5000 rpm, mass of 3.5 kg, AUV length of 2 m, diameter of 0.3 m, and displacement of 80 kg. On the basis of this platform, two in situ trials were carried out, respectively, in Mudeford harbor and Southampton water. From the experimental result, the maximum instantaneous generated power of this system is 3.58 W (Mudeford harbor trial, wave height of 0.1-0.15 m) and 2.86 W (Southampton water trial, wave height of 0.1 m), respectively, because of the relatively small wave in Southampton water. However, the average generated powers are very low; therefore, it is necessary to increase its power generation in further research, such as power take off (PTO) control, reducing friction, system operation optimization,85 etc.
Thermal energy is the heat energy stored because of the temperature gradient between the warm surface water and the cold deep water. Solar radiation is mostly absorbed by surface water, and only 1% energy can reach the water with depth of below 10 m. Therefore, the temperature of water decreases rapidly with the increasing depth, especially at the depth of 10 m, which will provide a possible energy source for the ocean robots. Figure 11 shows that average sea surface temperature decreases gradually from low to high latitudes, due to effects of solar radiation. Meanwhile, the temperature of sea water will generally drop to 5°C underwater of 1000 m.

2.5 | Transform thermal into electric energy

Researchers from NASA’s Jet Propulsion Laboratory, Scripps Institution of Oceanography, and University of California have firstly achieved success in demonstration of the robotic underwater vehicle SOLO-TREC, entirely powered by the ocean thermal energy, with 84-kg weight and 2-m height, as shown in Figure 12.

SOLO-TREC absorbs the ocean thermal energy when it alternately goes through the thermocline between warm surface and colder deep water. Then, the ocean thermal energy will be converted into electricity to recharge the vehicle’s batteries by a novel thermal recharging engine, which has 10 external tubes containing waxy substances (phase-change materials). As SOLO-TREC encounters the warm water, the phase-change material will melt and expand in volume, while as it dives in cold waters, the material will solidify and contract. Waxy material expansion pressurizes oil stored in thermal recharging engine, and the hydraulic motor is periodically driven to generate electricity. Furthermore, the vehicle's hydraulic system can change its volume and allow it to move up or down. SOLO-TREC has made more than 300 successful dives.
with a depth of 500 m. The thermal recharging engine can produce about 1.7 W·h of electricity per dive, enough to power the sensors, communications device, Global Positioning System (GPS), and buoyancy-control pump mounted on this vehicle. The thermal conversion technology of SOLO-TREC has been commercialized and has great promise in equipping most ocean robots, such as AUV and thermal UG.

2.5.2 Transform thermal into pressure energy

The thermal UG, SLOCUM, was firstly developed by Webb Research Corporation, obtaining propulsion power from the ocean thermocline through a heat engine system, which can provide the buoyancy change to enable the glider to ascend or descend. The heat harvested by the heat engine causes the change of the solid-liquid state of the working fluid, which will help the UG to realize the volume (or buoyancy) change. There are four stages to complete the thermodynamic cycle, as shown in Figure 13.

Figure 13A shows that heat engine is in a stable thermal equilibrium state in the warm surface water, with the nitrogen gas compressed. The buoyancy of the vehicle is slightly larger than the gravity because of the external bladder inflated and working fluid expanded. As illustrated in Figure 13B, with the three-way valve opened, external bladder and internal bladder will be connected,
and the transfer fluid in external bladder will flow into the internal bladder, so the glider will descent with its buoyancy reducing. As the vehicle reaches cold water, working fluid will start shrinking and contracting, and the transfer fluid from the internal bladder will flow into the energy exchanger. Figure 13C shows that with the three-way valve opened again, the pressurized transfer fluid will flow into the external bladder, and the vehicle will ascent for the change from negative to positive buoyancy. As shown in Figure 13D, when the vehicle ascends to warm surface waters, the working fluid absorbs heat to melt and expand, and glycol flows to recharge the accumulator. The vehicle returns to the initial state (Figure 13a), and the cycle is completed.

2.6 | Summary

As mentioned above, many MRE sources have been successfully equipped in ocean robots through certain technical means or devices, and many new concept ocean robots have also been developed and applied to ocean operations, as shown in Table 2.

3 | CHALLENGES

There is no doubt that MRE has promising application values in ocean robots, and many new concept ocean robots, powered by these energy resources, have been successfully developed, with more superior performance in endurance than traditional ocean robots. However, there are still many challenges and difficulties to be solved in the exploitation and utilization of MRE in ocean robots.

1. Environmental constraints. MRE is closely related to environmental conditions, which impose restrictions on the application of MRE in ocean robots. Besides, geographical location and unpredictable disturbances caused by weather changes will also greatly influence on the power supply of ocean robots. For instance, it is necessary for ocean robots on the ocean surface during the day to absorb solar energy, because it is not conducive for solar absorption at night, cloudy, or rainy weather or under water. Wind energy and wave energy have features of variability in their generation, direction, and speed in space and time, which are all uncertain because of weather changes. And the thermal energy is very unevenly distributed in the oceans and mainly determined by terrestrial latitude (affecting solar energy radiant quantity). Furthermore, harsh ocean environment and marine biological corrosion also pose challenges to the development of MRE. Thus, when it comes to the utilization of MRE in ocean robots, not only its engineering and technical problems should be considered, but also its working environment condition are also very important.

2. Low energy density. Although the ocean contains abundant MRE, its energy density is generally low, which raises the problem of technical realization and has important influence on the design of ocean robots. It is estimated that the power energy densities of solar, wind, and wave are only 0.1 to 0.2, 0.4 to 0.6, and 2 to 3 kW/m², respectively, which means that these ocean robots have to own enough area to absorb sufficient energy. Consequently, SAUV, USV, and UG have larger upper surface to enhance the solar energy absorption and commodiously install the solar panels. Analogously, wave glider acquires wave energy through its flat float body, which can transmit the wave motion to the UG body through the cable to the utmost extent and finally converting into driving force by UG body. Simultaneously, as the propulsion part of wind-powered sailboats, massive sails were equipped on the sailboat to transform

### TABLE 2  Summary of marine renewable energy (MRE) applied in ocean robots

| MRE                | Converted Energy Form | Ocean Robots | Specific Examples                                      |
|--------------------|-----------------------|--------------|-------------------------------------------------------|
| Solar energy       | Electric energy        | AUV, USV, and UG | SAUV II, SASV, SORA, and wave glider                   |
| Wind energy        | Mechanical energy      | Sailboat     | AVALON, WASP, N-boat, Saildrone, FAST                 |
| Wave energy        | Mechanical energy / Electric energy | USV and AUV | Wave glider, MHG, and AUV with gyroscopic system          |
| Thermal energy     | Electric energy / Pressure energy | UG, profiling float | SLOCUM and SOLO-TREC                                    |
| Tidal current energy | Electric energy       | AUV          | AUV with DATTs                                        |

Abbreviations: AUV, autonomous underwater vehicle; DATTs, diffuser-augmented tidal turbines; MHG, multifunction hybrid glider; SASV, solar-powered autonomous surface vehicle; SAUV, solar-powered autonomous underwater vehicle; UG, underwater glider; USV, unmanned surface vehicle.
the wind power into their driving force. Therefore, it can be seen that low energy density of MRE has great influence on the appearance design of ocean robots.

3. Low-energy utilization efficiency. The efficiency of the energy conversion devices in these ocean robots powered by MRE is generally low, which are related to many factors, such as its mechanical design, parameter optimization, external drag reduction, etc. Meanwhile, the power consumption of ocean robots is proportional to the cubic square of their speed. For this reason, many ocean robots driven by MRE have low motion speed. For instance, the average speed of wave glider is 1.5 knots in sea state 3, and UG generally has a speed of 0.5 to 1 knots. This will lead directly to their weak antiflow ability and environmental adaptability. Therefore, it becomes an important issue to improve energy utilization efficiency to increase the system's energy supply, which may be closely related to the introduction of new materials, new technology, and new methods.

4 | PROSPECTS

MRE has been the most promising choice for power supply of ocean robots, although they have some shortcomings, as represented in Sections 2 and 3. With the advance of marine science and technology, its development prospects demonstrate some new characteristics.

1. More comprehensive utilization of MRE. The utilization of MRE in ocean robots is closely related to their working environment, movement principle, energy form, and body structure, where the appropriate energy sources will be selected based on the above factors. For instance, it is very appropriate to introduce solar energy, wind energy, or wave energy in USV, because of its only moving on water surface where these energies are concentrated exactly. Similarly, UG and SOLO-TREC can move in the ocean vertical profiler between water surface and underwater; therefore, thermal energy is becomingly chosen to supply their energy consumption. In order to obtain more energy supply, multiple MRE sources will be selected and equipped on certain ocean robots. At present, many ocean robots have realized comprehensive utilization of energy. Autonomous sailboats, driven by wind energy to realize the zigzag trajectory on the ocean surface, are also installed solar panel to absorb solar energy to provide their electricity power, such as AVALON, FAST, Saildrone, etc. Meanwhile, wave glider is a new-concept ocean gliding robot, using wave energy to obtain driving force and solar energy to supplement its electricity consumption. The comprehensive utilization of MRE has become a research hotspot and applied to more and more ocean robots, which not only increases access to energy sources of ocean robots but also reduces the risk of energy supply uncertainty.

2. More new technologies to be introduced. As people keep a watchful eye on the development of MRE, it is confirmed that more and more new technologies will be referenced and equipped with ocean robots in near the future, such as new materials, new methods, new devices, etc. For example, phase-change materials have significant influence on the improvement of the energy utilization efficiency in the thermal UG, where it is very appropriate to choose high-volume change-rate materials in phase change at small temperature difference. Besides, batteries are commonly chosen to store energy for the time being, which have limited energy and always occupy most of the space and weight in these ocean robots. Therefore, new technology of efficient energy storage is very important for ocean robots, which can reduce the dependence of energy reserves on environmental conditions to some extent, such as solar energy for the rain days or night, wave, and wind energy for less wind weather. Furthermore, it is very necessary to introduce intelligent energy management system to surveille the working state of the batteries in real time. Given that ocean robots have been operating for a long time, intelligent energy management system can not only reasonably and timely charge and discharge and ensure the safety of energy storage but also improve their energy utilization efficiency.

3. Potential development of new-form marine energy. MRE is derived from the marine environment, including solar, wind, tides, waves, thermal, ocean currents, salinity gradients, and so on. These energy resources are all green, clean, and pollution-free, and they will play a critical role in alleviating the energy crisis in the future. Some of these energy sources have been applied successfully in ocean robots, while others are still being developed and tested, such as tides, ocean currents, salinity gradients, etc. Although some of these new energy sources have been already applied to generate electricity in factories, there are still many problems to be solved to power ocean robots. On the one hand, these energy conversion devices need to be miniaturized for installation; on the other, its energy conversion efficiency should be high enough to meet the basic energy
demands of the ocean robot. As presented in Section 2, Shi et al, from Newcastle University, have tried to apply tidal current energy to power electricity consumption of AUV board through twin turbines, and numerical optimization is validated by physical model tests. Although this technology has not been used in practical marine engineering, it is beneficial to the exploitation of new-form marine energy.

5 | CONCLUSIONS

As the activity processes for humans continue to progress in exploitation and exploration of the ocean, there is an urgent need for certain ocean robots with strong endurance to engage in long-range and long-time ocean operations or data collection, which will provide first-hand information for the further marine scientific research. The introduction of MRE provides the possibility to solve the problem of energy supply, a major constraint on endurance of these ocean robots. It is gratifying that some outstanding achievements have been made in the utilization of MRE through the continuous efforts of researchers around the world, such as SAUV II (powered by solar energy), Saildrone (driven by wind energy), SOLO-TREC (powered by thermal energy), wave glider (driven by wave energy), etc. These ocean robots are fully capable of extracting energy from their surrounding environment, which is of great importance to improve their performance to meet the demands of different marine science applications. It is obvious that these ocean robots powered by MRE may replace the traditional marine development tool in certain future marine applications, because of their low cost, unattended operation, and high efficiency, such as manned ships, buoys in ocean observation. At present, the proven technique of MRE mainly focuses on energy sources presented in Section 2. It is believed that more and more new-form marine energy will be developed and a growing number of new technologies or devices will be applied to ocean robots.

ACKNOWLEDGEMENTS

This work is supported by the National Natural Science Foundation of China (grant no. 51809127), State Key Laboratory of Mechanical Transmissions (grant no. SKLMT-KFKT-201712), Natural Science Foundation of Jiangsu Province (grant no. BK20170577), and State Key Laboratory of Robotics (grant no. 2017-O06).

CONFLICT OF INTEREST

Baoqiang Tian and Jiancheng Yu declare that they have no conflict of interest.

ORCID

Baoqiang Tian https://orcid.org/0000-0003-4287-5377

REFERENCES

1. Sen Z. Solar Energy Fundamentals and Modeling Techniques: Atmosphere, Environment, Climate Change and Renewable Energy. London: Springer-Verlag; 2008.
2. Borthwick AGL. Marine renewable energy seascape. Engineering. 2016;2(1):69-78.
3. Inzartsev AV. Underwater vehicles: in-tech; 2009.
4. Roberts G, Sutton R. Advances in Unmanned Marine Vehicles. Institution of Engineering and Technology: London, UK; 2006.
5. Chen Z, Yu J, Zhang A. Overview on observation-oriented unmanned marine vehicles with high cruising ability: development status and prospect. J Ocean Technol. 2016;35:122-130.
6. Wang X, Shang J, Luo Z, Tang L, Zhang X, Li J. Reviews of power systems and environmental energy conversion for unmanned underwater vehicles. Renew Sustain Energy Rev. 2012;16:1958-1970.
7. Alaaeldeen MEA, Duan W-Y. Overview on the development of autonomous underwater vehicles (AUVs). Chuan Bo Li Xue/J Ship Mech. 2016;20:768-787.
8. Chen Q. Unmanned Underwater Vehicle. 1st ed. Beijing: National Defense Industry Press; 2014.
9. Sawa T, Kasaya T, Hyakudome T, Yoshida H. Natural resource exploration with sonar on underwater vehicle. In: ASME 2012 31st International Conference on Ocean, Offshore and Arctic Engineering, OMAE 2012, July 1, 2012 - July 6, 2012. Rio de Janeiro, Brazil: American Society of Mechanical Engineers (ASME); 2012.
10. Yoshida H, Hyakudome T, Ishibashi S, et al. An autonomous underwater vehicle with a canard rudder for underwater minerals exploration. In: 2013 10th IEEE International Conference on Mechatronics and Automation, IEEE ICMA 2013. August 4, 2013 - August 7, 2013. Takamastu, Japan: IEEE Computer Society; 2013.
11. Yokota S, Kim K, Imasato M, et al. Development and sea trial of an autonomous underwater vehicle equipped with a sub-bottom profiler for surveying mineral resources. In: 2016 Autonomous Underwater Vehicles. AUV 2016, November 6, 2016 - November 9, 2016. Tokyo, Japan: Institute of Electrical and Electronics Engineers Inc.; 2016.
12. Dumke I, Nornes SM, Purser A, et al. First hyperspectral imaging survey of the deep seafloor: high-resolution mapping of manganese nodules. Remote Sens Environ. 2018;209:19-30.
13. Stansfield K, Smeed DA, Gasparini GP, et al. Deep-sea, high-resolution, hydrography and current measurements using an autonomous underwater vehicle: the overflow from the Strait of Sicily. Geophys Res Lett. 2001;28(13):2645-2648.
14. Brown HC, Jenkins HK, Meadows GA, Shuchman RA. BathyBoat: an autonomous surface vessel for stand-alone survey and underwater vehicle network supervision. *Mar Technol Soc J.* 2010;44(4):20-29.

15. Breivik GM, Fjordin SA, Skotheim O. Robust pipeline localization for an autonomous underwater vehicle using stereo vision and echo sounder data. In: *Intelligent Robots and Computer Vision XXVII: Algorithms and Techniques, January 18, 2010 - January 19, 2010.* San Jose, CA, United States: SPIE:2010.

16. Khan A, Ali SAA, Meriaudeau F, Malik AS, Soon LS, Seng TN. Visual feedback based heading control of autonomous underwater vehicle for pipeline corrosion inspection. *Int J Adv Rob Syst.* 2017;14(3):172988141665817.

17. Goodman L, Levine ER, Wang Z. Subsurface observations of surface waves from an autonomous underwater vehicle. *IEEE J Ocean Eng.* 2010;35(4):779-784.

18. Rudnick DL. Ocean research enabled by underwater gliders. In: Carlson CA, Giovannoni SJ, eds. *Annual Review of Marine Science, Vol 8.* Vol.8; 2016:519-44.

19. Hwang A, Seong W. Simultaneous mapping and localization for small military unmanned underwater vehicle. *Def Sci J.* 2012;62(4):223-227.

20. McMahon J, Plaku E. Autonomous underwater vehicle mine countermeasures mission planning via the physical traveling salesman problem. In: *MTS/IEEE Washington, OCEANS 2015, October 19, 2015 - October 22, 2015.* Washington, DC, United states: Institute of Electrical and Electronics Engineers Inc.; 2015.

21. Hamilton MJ, Kenna S, Hughes D. Antisubmarine warfare applications for autonomous underwater vehicles: the GLINT09 sea trial results. *J Field Rob.* 2010;27(6):890-902.

22. Kenna S, Hamilton MJ, Hughes DT, LePage KD. Adaptive autonomous underwater vehicles for littoral surveillance. *Intell Serv Robot.* 2011;4(4):245-258.

23. Letcher TM. *Future Energy: Improved, Sustainable and Clean Options for Our Planet.* Amsterdam: Elsevier; 2008.

24. Steinfield A, Palumbo R. Fuels from sunlight and water. *Sun at Work in Eur.* 1997:12:8-10.

25. Komerska RJ, Chappell SG. A simulation environment for testing and evaluating multiple cooperating solar-powered AUVs. In: *OCEANS 2006, September 18, 2006 - September 21, 2006.* Boston, MA, United states: Inst. of Elec. and Elec. Eng. Computer Society; 2006.

26. Arima M, Takeuchi A. Development of an autonomous surface station for underwater passive acoustic observation of marine mammals. In: *OCEANS 2016 - Shanghai.* Shanghai, China: Institute of Electrical and Electronics Engineers Inc.; 2016.

27. Higinbotham JR, Moisan JR, Schirzinger C, Linkswiler M, Yungel J, Orton P. Update on the development and testing of a new long duration solar powered autonomous surface vehicle. In: *OCEANS 2008, September 15, 2008 - September 18, 2008.* Quebec City, QC, Canada: IEEE Computer Society; 2008.

28. Arima M, Yoshida K, Tonai H. Development of a coral monitoring system for the use of underwater vehicle. In: *OCEANS 2014 MTS/IEEE Taipei Conference: Oceans Regeneration, April 7, 2014 - April 10, 2014.* Taipei, Taiwan: Institute of Electrical and Electronics Engineers Inc.; 2014.

29. Arima M, Blidberg DR. Current progress in the development of a solar powered autonomous underwater vehicle (AUV). In: *International Symposium on Underwater Technology, UT 1998, April 15, 1998 - April 17, 1998.* Tokyo, Japan: Institute of Electrical and Electronics Engineers Inc.; 1998.

30. Balbert JC, Irazoqui-Pastor P, Miles S, Blidberg DR, James D, Agee MD. Solar AUV technology evaluation and development project. In; 1997.

31. Agee MD, Blidberg DR, Balbert J, Melchin CJ, Troop DP. Results of the evaluation and testing of the solar powered AUV and its subsystems. In: *Proceedings of the 2002 Workshop on Autonomous Underwater Vehicles, June 20, 2002 - June 21, 2002.* San Antonio, TX, United states: Institute of Electrical and Electronics Engineers Inc.; 2002.

32. Blidberg D, Muppaparu S, Chappell S, Komerska R, Balbert JC, Nitzel R. The SAUV II (solar powered AUV) test results 2004. In: *OCEANS 2005 - Europe, June 20, 2005 - June 23, 2005.* Brest, France: Institute of Electrical and Electronics Engineers Computer Society; 2005.

33. Balbert J, Baker J, Duchesney J, et al. A solar-powered autonomous underwater vehicle. In: *Celebrating the Past... Teaming Toward the Future, September 22, 2003 - September 26, 2003.* San Diego, CA., United states: Institute of Electrical and Electronics Engineers Inc; 2003.

34. Arima M, Okashima T, Yamada T. 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: IEEE Computer Society; 2011.

35. Hwee HN, Singh P. Modeling and optimization of a hybrid power system for an unmanned surface vehicle. *J Power Sources*. 2012:198:368-377.

36. Arima M, Okashima T, Yamada T. Development of a solar-powered underwater vehicle. In: *22nd International Offshore and Polar Engineering Conference, ISOPE-2012, June 17, 2012 - June 22, 2012.* Rhodes, Greece: International Society of Offshore and Polar Engineers; 2012.

37. Arima M, Tonai H. Feasibility study of an ocean-going solar-powered underwater glider. In: *24th International Ocean and Polar Engineering Conference, ISOPE 2014 Busan, June 15, 2014 - June 20, 2014.* Busan, Korea, Republic of: International Society of Offshore and Polar Engineers; 2014.

38. Burton T, Sharpe D, Jenkins N. *Wind Energy Handbook.* John Wiley & Sons Ltd: Chichester, England; 2011.

39. Guo Q, Xu X, Zhang K, et al. Assessing global ocean wind energy resources using multiple satellite data. *Remote Sens (Basel).* 2018;10(2).
42. Ryenne PF, von Ellenrieder KD. Unmanned autonomous sailing: current status and future role in sustained ocean observations. *Mar Technol Soc J*. 2009;43(1):21-30.

43. Ryenne PF, von Ellenrieder KD. Development and preliminary experimental validation of a wind- and solar-powered autonomous surface vehicle. *IEEE J Ocean Eng*. 2010;35(4):971-983.

44. Erckens H, Busser G-A, Pradalier C, Siegwart RY. Avalon: navigation strategy and trajectory following controller for an autonomous sailing vessel. *IEEE Robot Autom Mag*. 2010;17(1):45-54.

45. Ryenne PF, Von Ellenrieder KD. A wind and solar-powered autonomous surface vehicle for sea surface measurements. In: *OCEANS 2008, September 15, 2008 - September 18, 2008*. Quebec City, QC, Canada: IEEE Computer Society; 2008.

46. Da Silva Junior AG, De Lima SA ST, Dos Santos DH, et al. Towards a real-time embedded system for water monitoring installed in a robotic sailboat. *Sensors (Switzerland)*. 2016;16(8):1226.

47. Cokelet ED, Meinic C, Lawrence-Slavas N, et al. The use of Saildrones to examine spring conditions in the Bering Sea. In: *MTS/IEEE Washington, OCEANS 2015, October 19, 2015 - October 22, 2015*. Washington, DC, United States: Institute of Electrical and Electronics Engineers Inc.; 2015.

48. Alves JC, Cruz NA. A mission programming system for an autonomous sailboat. In: *2014 Oceans - St. John’s, OCEANS 2014, September 14, 2014 - September 19, 2014*. St. John’s, NL, Canada: Institute of Electrical and Electronics Engineers Inc.; 2015.

49. Alves JC, Ramos TM, Cruz NA. A reconfigurable computing system for an autonomous sailboat. *OGAI J (Oesterreichische Gesellschaft fuer Artificial Intelligence)*. 2008;27:18-24.

50. Cruz NA, Alves JC. Autonomous sailboats: an emerging technology for ocean sampling and surveillance. In: *OCEANS 2008, September 15, 2008 - September 18, 2008*. Quebec City, QC, Canada: IEEE Computer Society; 2008.

51. Cruz NA, Alves JC. Auto-heading controller for an autonomous sailboat. In: *OCEANS’10 IEEE Sydney, OCEANSSYD 2010, May 24, 2010 - May 27, 2010*. Sydney, NSW, Australia: IEEE Computer Society; 2010.

52. Cruz NA, Alves JC. Navigation performance of an autonomous sailing robot. In: *2014 Oceans - St. John’s, OCEANS 2014, September 14, 2014 - September 19, 2014*. St. John’s, NL, Canada: Institute of Electrical and Electronics Engineers Inc.; 2015.

53. Vilas Boas JM, Silva AG, Santos DH, Negreiros APF, Alvarez-Jacobo JE, Goncalves LMG. Towards the electromechanical design of an autonomous robotic sailboat. In: *13th Latin American Robotics Symposium and 4th Brazilian Symposium on Robotics, LARS/SBR 2016, October 8, 2016 - October 12, 2016*. Recife, Pernambuco, Brazil: Institute of Electrical and Electronics Engineers Inc.; 2016.

54. Santos DH, Negreiros APF, Jacobo JEA, Goncalves LMG, Silva AG, Silva JMVBS. Short-term path planning for high-level navigation control of N-boat—the sailboat robot. In: *13th Latin American Robotics Symposium and 4th Brazilian Symposium on Robotics, LARS/SBR 2016, October 8, 2016 - October 12, 2016*. Recife, Pernambuco, Brazil: Institute of Electrical and Electronics Engineers Inc.; 2016.

55. Santos D, Silva Junior GA, Negreiros A, et al. Design and implementation of a control system for a sailboat robot. *Robotics*. 2016;5(1):5.

56. Mordy CW, Cokelet ED, Robertis AD, et al. Advances in ecosystem research: Saildrone surveys of oceanography, fish, and marine mammals in the Bering Sea. *Oceanography*. 2017;30:113-115.

57. Khan N, Kalair A, Abas N, Haider A. Review of ocean tidal, wave and thermal energy technologies. *Renew Sustain Energy Rev*. 2017;72:590-604.

58. Lisboa AC, Vieira TL, Guedes LSM, Vieira DAG, Saldanha RR. Optimal analytic dispatch for tidal energy generation. *Renew Energy*. 2017;108:371-379.

59. Manuel Gonzalez-Caballin J, Alvarez E, Jose Gutierrez-Trashorras A, Navarro-Manso A, Fernandez J, Blanco E. Tidal current energy potential assessment by a two dimensional computational fluid dynamics model: the case of Aviles port (Spain). *Energy Conv Manag*. 2016;119:239-245.

60. Zhang J-S, Wang J, Tao A-F, Zheng J-H, Li H. New concept for assessment of tidal current energy in Jiangsu Coast, China. *Adv Mech Eng*. 2013;5:340501.

61. Uihlein A, Magagna D. Wave and tidal current energy—a review of the current state of research beyond technology. *Renew Sustain Energy Rev*. 2016;58:1070-1081.

62. Shi W, Wang D, Atlar M, Guo B, Seo K-C. Optimal design of a thin-wall diffuser for performance improvement of a tidal energy system for an AUV. *Ocean Eng*. 2015;108:1-9.

63. McCormick ME. *Ocean Engineering Mechanics With Application*. New York: Cambridge University Press; 2010.

64. Falnes J. A review of wave-energy extraction. *Mar Struct*. 2007;20(4):185-201.

65. López I, Andreu J, Ceballos S, Martinez de Alegría I, Kortabarria I. Review of wave energy technologies and the necessary power-equipment. *Renew Sustain Energy Rev*. 2013;27:413-434.

66. Cornett AM. A global wave energy resource assessment. In: *18th 2008 International Offshore and Polar Engineering Conference, ISOPE 2008, July 6, 2008 - July 11, 2008*. Vancouver, BC, Canada: International Society of Offshore and Polar Engineers; 2008.

67. Sabzehgar R, Moallem M. A review of ocean wave energy conversion systems. In: *2009 IEEE Electrical Power & Energy Conference (EPEC)*. Montreal, QC, Canada: Institute of Electrical and Electronics Engineers Inc.; 2009.

68. Falcão AFdO. Wave energy utilization: a review of the technologies. *Renew Sustain Energy Rev*. 2010;14(3):899-918.

69. Sakagami N, Terao Y. Development of a measurement and instrumentation of a control system for a sailboat robot. *Proc MTS/IEEE Oceans*. 2009;2009:1-6.

70. Hine R, Willcox S, Hine G, Richardson T. The wave glider: a wave-powered autonomous marine vehicle. *Proc MTS/IEEE Oceans*. 2009;2009:1-6.

71. Manley J, Willcox S. The wave glider: a new concept for deploying ocean instrumentation. *IEEE Instrum Meas Mag*. 2010;13(6):8-13.
72. Tian B, Yu J, Zhang A. Dynamic modeling of wave driven unmanned surface vehicle in longitudinal profile based on D-H approach. *J Cent South Univ*. 2015;22(12):4578-4584.

73. Villareal TA, Wilson C. A comparison of the Pac-X trans-Pacific wave glider data and satellite data (MODIS, Aquarius, TRMM and VIIRS). *PLoS One*. 2014;9(3):e92280.

74. Meyer Gutbrod EL, Greene CH, McGarry LP. Wave glider technology for fisheries research new integrated instrumentation expands the fisheries acoustics toolbox. *Sea Technol*. 2015;56:15-19.

75. Manley JE, Hine G. Unmanned surface vessels (USVs) as tow platforms: wave glider experience and results. In: *Proceedings of MTS/IEEE Oceans 2016*. Monterey, CA, United states: Institute of Electrical and Electronics Engineers Inc.; 2016.

76. Wiggins S, Manley J, Brager E, Woolhiser B. Monitoring marine mammal acoustics using wave glider. In: *Proceedings of MTS/IEEE Oceans 2010*. Seattle, WA, USA: Institute of Electrical and Electronics Engineers Inc.; 2010.

77. Maqueda MAM, Penna NT, Williams SDP, Foden PR, Martin I, Pugh J. Water surface height determination with a GPS wave glider: a demonstration in Loch Ness, Scotland. *J Atmos Oceanic Tech*. 2016;33(6):1159-1168.

78. Amiruddin SM. 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*. Kuala Lumpur, Malaysia: Institute of Physics Publishing; 2016.

79. Van Lancker V, Baeye M. Wave glider monitoring of sediment transport and dredge plumes in a shallow marine sandbank environment. *PLoS One*. 2015;10(6):e0128948.

80. Willcox S, Meinig C, Sabine CL, et al. An autonomous mobile platform for underway surface carbon measurements in open-ocean and coastal waters. In: *Proceedings of MTS/IEEE Oceans 2009*. Biloxi, MS; 2009.

81. Frolov S, Bellingham J, Anderson W, Hine G. Wave glider—a platform for persistent monitoring of algal blooms. In: *Proceedings of MTS/IEEE Oceans 2011*. Kona, Hawaii: IEEE; 2011.

82. Mitarai S, McWilliams JC. Wave glider observations of surface winds and currents in the core of typhoon Danas. *Geophys Res Lett*. 2016;43(21):11,312-311,319.

83. Lenain L, Melville WK. Autonomous surface vehicle measurements of the ocean’s response to tropical cyclone Freda. *J Atmos Oceanic Tech*. 2014;31(10):2169-2190.

84. Tian B, Zhou W, Li L, Yao Z. Research on realization mechanisms of multifunctional hybrid glider. In: *Proceedings of MTS/IEEE Oceans 2016*. Shanghai, China: Institute of Electrical and Electronics Engineers Inc.; 2016.

85. Townsend N. In situ results from a new energy scavenging system for an autonomous underwater vehicle. In: *OCEANS 2016 MTS/IEEE Monterey*. Monterey, CA, USA: Institute of Electrical and Electronics Engineers Inc.; 2016.

86. Townsend N, Shenoi A. Recharging autonomous underwater vehicles from ambient wave induced motions. In: *2013 OCEANS - San Diego*. San Diego, CA, USA: Institute of Electrical and Electronics Engineers Inc.; 2013.

87. Townsend NC, Shenoi RA. Feasibility study of a new energy scavenging system for an autonomous underwater vehicle. *Auton Robot*. 2015;1-13.

88. Cai L. Performance evaluation and parametric optimum design of an updated ocean thermal energy conversion system. *Ocean Eng*. 2016;117:254-258.

89. https://upload.wikimedia.org/wikipedia/commons/2/21/WOA09_sea-surf_TMP_AYool.png.

90. Smith RN, Huynh VT. Controlling buoyancy-driven profiling floats for applications in ocean observation. *IEEE J Ocean Eng*. 2014;39(3):571-586.

91. Smith RN, Dunbabin M. Controlled drift: an investigation into the controllability of underwater vehicles with minimal actuation. In: *2011 Australasian Conference on Robotics and Automation, December 7, 2011 - December 9, 2011*. Melbourne, VIC, Australia: Australian Robotics and Automation Association Inc.; 2011.

92. Chao Y. Autonomous underwater vehicles and sensors powered by ocean thermal energy. In: *OCEANS 2016 - Shanghai*. Shanghai, China: Institute of Electrical and Electronics Engineers Inc.; 2016.

93. Webb DC, Simonetti PJ, Jones CP. SLOCUM: an underwater glider propelled by environmental energy. *IEEE J Ocean Eng*. 2001;26(4):447-452.

**How to cite this article:** Tian B, Yu J. Current status and prospects of marine renewable energy applied in ocean robots. *Int J Energy Res*. 2019;43:2016-2031. [https://doi.org/10.1002/er.4371](https://doi.org/10.1002/er.4371)