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On technical issues for underwater charging of robotic fish schools using ocean renewable energy

Liuchao Jin[a,b] and Weicheng Cui[b]

[a]Pittsburgh Institute, Sichuan University, Chengdu, People's Republic of China; [b]Key Laboratory of Coastal Environment and Resources of Zhejiang Province (KLaCER), School of Engineering; Westlake University, Hangzhou, People's Republic of China

ABSTRACT
Robotic fish will become the next generation of submersibles due to their advantages of high propulsion efficiency, high mobility, excellent environmental compatibility and good load capacity. However, short battery life and high charging costs would be the main obstacles restricting the deployment of robotic fish for long–term ocean monitoring and cruises. The present methods of either using a mother ship or laying cables are very expensive. In order to greatly reduce the cost, a nearby cheap charging station is necessary. In this paper, a comprehensive review of underwater automatic charging methods and systems for robotic fish based on the existing marine renewable energy conversion technology is carried out, including robotic fish underwater docking and charging technology. Based on the review and comparative analysis, a design idea for a novel and feasible system for underwater charging for a school of robotic fish through renewable energy is proposed.

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KEYWORDS
Robotic fish; underwater docking; underwater charging; remote operation; marine renewable energy.

1. Introduction

Nature has always been a source of inspiration for various human sciences and technologies, engineering principles, and major innovations and inventions. There are many mechanisms in nature that are worth imitating. People learn from the ultrasonic waves of bats and use radar to detect the environment (Carrer and Bruzzone 2016); scientists study the eyes of frogs (Tang et al. 2014), thus inventing electronic frog eyes; inspired by birds flying in the sky, humans build airplanes (Mohler 2004). Robotic fish are also a good example of humans learning from nature. The earth is a planet whose surface is covered 71% by water, and fish are the masters of this water world. As of 2019, there are more than 36,000 species of fish in the world, which account for most of the named vertebrates (Rome 2020). Fish have many characteristics that attract us to imitate them. For example, high mobility and agility, considerably high evading speeds, small turning radius and also maintaining balance even in rough water and travelling freely (Webb et al. 1996). Robotic fish combine these characteristics of fish, making them have good performance in ocean exploration and monitoring.

Compared with Autonomous Underwater Vehicles (AUVs), which are commonly used for underwater detection and monitoring nowadays, robotic fish have advantages in many aspects. First, the propulsion efficiency of robotic fish can reach 80% (Liang et al. 2011), which is much higher than that of the ordinary AUV. The AUV is driven by propellers, whose efficiency is relatively low–at most 40% to 60% (Lidtke et al. 2021). Hence, robotic fish can save energy and conduct more operations under the same battery capacity (Shen et al. 2016), greatly enhancing their working ability and expanding their working area. Besides, the turning radius of the AUV is relatively large, which can be two times of their body length (Anderson and Kerrebrock 1997). In contrast, the turning radius of the robotic fish can be one-fifth of their body length (Chen X et al. 2018), which greatly increases their manoeuvrability and flexibility (Yang Z et al. 2022; Howe et al. 2021). Moreover, because the robotic fish do not have a propeller, they do not produce much noise compared to the AUV (Wang Z et al. 2022), which leads to the robotic fish having a very good performance not only on the concealment in the military field but also on the friendliness to marine life.

It is precisely because of these excellent characteristics of robotic fish that they have great potential in the fields of pollution detection (Hu et al. 2011), water quality monitoring (Zhang M et al. 2020b), underwater exploration (Chen S-F and Yu 2014), oceanic supervision (Zhang M et al. 2020a) and fishery conservation (Katzschmann et al. 2018). As the technology of robotic fish gradually matures in the future, they will replace the AUV in many fields and become the main force of underwater robots.

In many cases, the application of robotic fish is often clustered (Landgraf et al. 2013; Shen and Guo 2015; Yan S et al. 2015; Joordens and Jamshidi 2018; Connor et al. 2019; Zhang Z et al. 2021). This is because when robotic fish are conducting underwater search and rescue, the cooperation and interaction of many robotic fish can greatly improve the efficiency of search and rescue. This kind of phenomenon is called swarm intelligence (Hassanien and Emary 2018). However, swarms of robotic fish will also result in a lot of difficulties, in which charging is one of the urgent problems to be solved (Shree et al. 2013). The use of robotic fish is often subject to severe power restrictions, which limits the duration of their deployment. In many cases, the working area of robotic fish is far from the coast, where it is off-grid. The use of ships or wired cables to charge robotic fish not only increases the cost but also largely limits their manoeuvrability and durability, especially for surveillance, persistent monitoring and inspections of sub-sea infrastructure (Copping et al. 2018). Every time, the robotic fish are about to run out of energy, they need to return to the ship for energy replenishment, which restricts the operation area and seabed detection efficiency. Therefore, it is a very good idea to use renewable energy from the ocean to charge the school of robotic fish. Marine

CONTACT Weicheng Cui ✉ cuiweicheng@westlake.edu.cn

Renewable Energy (MRE) can be harvested offshore so that it can continuously provide energy for the robotic fish swarms that work far away from the coastline. The wave power buoy is an excellent candidate for the energy source of robotic fish. The wave power buoy is a kind of equipment that converts the wave energy into electric energy and stores it in the battery (Ji et al. 2021). When robotic fish need energy, they can go there to recharge without any human intervention.

This review aims to summarise recent advances in underwater charging of robotic fish schools using ocean renewable energy from five aspects–marine renewable energy, robotic fish, underwater docking techniques of robotic fish, underwater charging platform of robotic fish and charging methods of robotic fish. Combining the pros and cons of the technologies in each aspect, we propose a feasible methodology for underwater charging of robotic fish schools using ocean renewable energy to facilitate the development of these technologies. The remainder of this paper is organised as follows. In Section 2.1, the resource distribution, the reserves, the development status, and the prospects of MRE will be introduced. Based on the current technique, in Section 2.2, the technical issues of the equipment for converting MRE into electricity will be studied. Next, the development of robotic fish will be examined in Section 3. Then, the existing methods for docking and charging of robotic fish will be explored in Section 4 and 5, respectively. Finally, based on the analysis on the research status of the MRE conversion and the robotic fish modelling, docking and charging, a conceptual design for underwater charging of robotic fish using MRE by combining the techniques of different processes is presented in Section 6 which might be useful for readers continual study based on our review.

2. Marine renewable energy resource

In this section, the development status and prospects of the energy resource–MRE are investigated in Section 2.1, and also the techniques to convert it into electricity are studied in Section 2.2.

2.1. The development status and prospects of marine renewable energy

MRE has huge reserves on the earth, which can fully meet all human energy needs (Yang Z and Copping 2017). Because MRE is cleaner and environmentally friendly than traditional fossil fuels, more and more people pay attention to it recently. They hope to achieve the goal of mitigating and ameliorating the problems of global warming and climate change through the application of the MRE.

MRE can include offshore wind energy (Clark et al. 2022), offshore solar energy (Kumar et al. 2015), wave energy (Thorpe 2000), tide energy (de Lavergne et al. 2019), current energy (Bahaj 2013), temperature difference energy (Xia et al. 2017) and salinity gradient energy (Seyfried et al. 2019). Offshore wind energy and offshore solar energy have played an important role in the recent development of the MRE. There are already many offshore wind and solar power generating groups around the world (Bedard et al. 2010). In addition, the development of tidal energy and current energy is also very rapid in recent years. Compared with tidal and current energy, the potentials of wave energy are relatively low but still have a lot of space for development (Wang Z et al. 2019). There are a lot of equipment invented to harvest the wave energy from the ocean and convert it into electricity that can supply to swarms of robotic fish (Dhanak and Xiros 2016). However, ocean thermal energy and salinity gradient energy generations are relatively not well developed at least for now so they will not be discussed in this paper (Bahaj 2011).

However, MRE also has shortcomings like unpredictable and intermittent (O'Rourke et al. 2010). For example, tidal energy has its own cycle varying from diurnal (once per day) and semi-diurnal (twice daily), to fortnightly (spring-neap) timescales (Neill and Hashemi 2018). Consequently, in order to improve the feasibility to use MRE to power the grid or existing maritime sectors for a long time, it is a good choice to equip each power generation device with batteries, which can greatly enhance the stability and continuity of electrical output. This provides a good condition for charging robotic fish with MRE.

From the exploration in this subsection, it can be seen that MRE is very rich in resources on the earth. In the future, under the background that the world pays more attention to climate change, MRE is likely to usher in its growth period. More and more MRE will be developed and utilised by humans, which also provides a strong prospect for us to study the use of MRE to realise the underwater charging of robotic fish.

2.2. Technical issues of marine renewable energy converter

Because most tidal energy conversion devices need to have a terrain difference to store the water level difference formed by the tide (Gorlov et al. 2001), the general tidal energy converter is generally built near the coast. Therefore, this converter is not suitable for charging robotic fish far away from the coastline. On the contrary, the wave energy and solar energy conversion devices are small in size and can be placed on the sea away from the coast. Therefore, this subsection will focus on the wave energy conversion device to prepare for the design of a complete set of robotic fish underwater charging technology that utilises MRE.

The development of wave energy converters (WEC's) started in the 1800s. It wasn't until Salter (1974) discovered the huge potential of wave energy in 1974 that people's research on wave energy began to explode. Up to now, wave energy converters are divided into eight categories according to their main working principles: attenuator, point absorber, oscillating wave surge converter, oscillating water column, overtopping/terminator device, submerged pressure differential, bulge wave and rotating mass (Pecher and Kofoed 2017). Figure 1 shows one of the designs for wave energy converters. Although different wave energy converters have different main working principles, the principles of power generation are similar: the kinetic energy contained in wave energy drives the rotor of the generator to rotate to generate electrical energy.

General wave energy converters can be simplified into the following model: a buoy is floating on the sea, to which a fixed buoy anchor is connected. The electric energy conversion device is placed in the buoy and connected to the energy storage device. The wave power generation device is placed under the sea surface and connected to the electrical energy conversion device. The electric energy conversion device stores the electric energy generated by the wave power generation device into an energy storage device and the stored energy is used for charging the robotic fish. Such a unified MRE conversion device model greatly simplifies the design of an energy absorption device that uses MRE to charge robotic fish underwater. When the underwater charging system for robotic fish is designed using MRE, this model as a charging terminal can be utilised for the robotic fish.

In conclusion, the existing MRE conversion technology is very mature and can roughly meet the needs for designing energy harvesting devices to use MRE to charge robotic fish underwater.

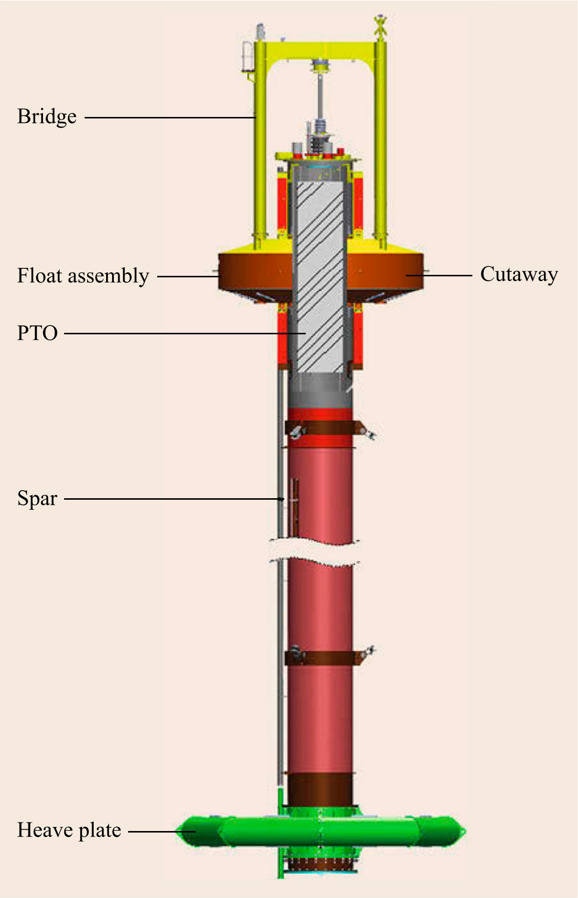
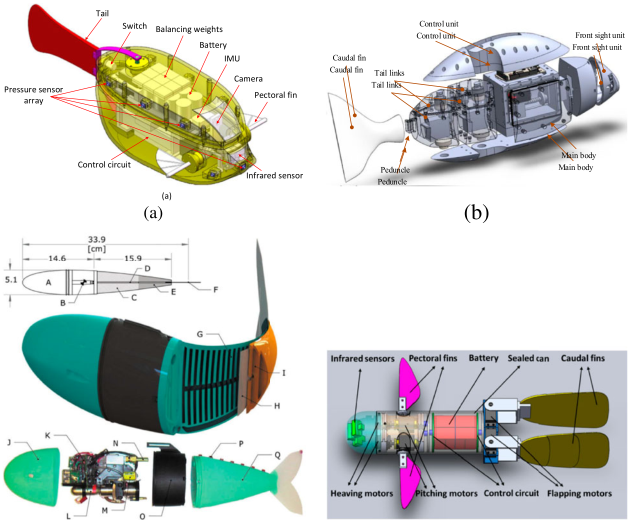


Figure 1. Sketch for Wave Energy Converters (WEC's) (Bellingham 2016). (This figure is available in colour online.)



(a) (b)

(c) (d)

Figure 2. Development of Robotic Fish. (a) Single Joint (SJ) Robotic Fish (Wang W et al. 2015). (b) Multi-Joint (MJ) Robotic Fish (Ay et al. 2018). (c) Smart Material-Based Design (Marchese et al. 2014). (d) Hybrid Design of BCF and MPF (Zhang S et al. 2016). (This figure is available in colour online.)

3. Technical issues in the development of robotic fish

In this section, the development of robotic fish based on the existing research and prototype is explored. Since the first robotic fish, RoboTuna, was developed at the Massachusetts Institute of Technology in 1994 (Stix 1994), the research on robotic fish has attracted more and more attention. Up to now, the research on robotic fish is still very active. Currently, there are many criteria for the classification of robotic fish, some are by shape and appearance, some are by control method, and some are by battery type. In this review, the existing robotic fish can be divided into two categories based on the body part utilised for propulsion: Body and/or Caudal Fin (BCF) propulsion and Median and/or Paired Fin (MPF) propulsion (Duraisamy et al. 2019; Sfakiotakis et al. 1999; Li Y et al. 2022; Sun B et al. 2022). Almost all kinds of robotic fish can be divided into these two categories. These two driving styles have their own advantages. The BCF propulsion system is inherently stable and is very suitable for long-term cruises at relatively high speeds, while the MPF propulsion system has the advantage of manoeuvrability and is usually used for small fish that require elegant grooming patterns (Yu et al. 2018).

Many people have studied both types of robotic fish. BCF robotic fish can be divided into three categories: Single Joint (SJ), Multi-Joint (MJ) and None-Joint (NJ) (Xie et al. 2021). For the single-joint design as shown in Figure 2(a), Zhou et al. (2010) modelled a miniature biomimetic robotic fish in a compact structure, with high manoeuvrability and multiple sensors. Li H et al. (2019) researched an underwater robotic fish using the single joint flexible caudal fin as a propeller for the inspection process of petroleum pipeline. Lu et al. (2021) produced a flexible-tail robotic fish with a single motor, whose speed can achieve 1.12 body lengths per second. For the multi-joint design as shown in Figure 2(b), Liu J and Hu (2010) described carangiform fish-like swimming motion for multi-joint robotic fish so that they can obtain fish-like behaviour and imitate the body movements of carangiform fish. Liang et al. (2011) presented a two-joint robotic fish for application in real-world scenarios. Chen D et al. (2020) proposed a novel compliant joint with two identical torsion springs for a biomimetic multi-joint robotic fish. Zhong et al. (2017) designed a novel robot fish with the combination of an active wire-driven body with a soft compliant tail to accomplish undulatory swimming. Dai et al. (2023) investigated a multi-joint robotic fish, an under-actuated system using the adaptive sight-line 3-D path-following based on the barrier. Zuo et al. (2021) put forward a robotic fish with 3-joint, driven through a double-slider-crank caudal fin. This robotic fish can achieve speeds of 0.98 body lengths per second. For the non-joint design, most of which is actuated by smart material-based design as shown in Figure 2(c), the structure of the first robotic fish, RoboTuna, was powered by ionic polymer metal composites (IPMC) (Stix 1994). Aureli et al. (2009) modelled free-locomotion of underwater vehicles actuated by IPMC. Chen Z et al. (2019) designed the robotic fish propelled by a servo motor and IPMC hybrid tail. Safari et al. (2022) produced a wirelessly powered robotic fish based on IPMC muscle. Chen D et al. (2018) developed a soft robotic fish with BCF propulsion using macro fibre composites smart materials. Zhao Q et al. (2021) fabricated a double caudal fin micro-robotic fish actuated by two piezoelectric bimorph cantilevers made of rigid carbon fibre/resin composites and flexible polyimide hinges. Zhao W et al. (2018) developed a soft robotic fish using piezoelectric fibre composite (PFC) as a flexible actuator. Scaradozzi et al. (2017) described an autonomous soft-bodied robot that is both self-contained and capable of rapid, continuum-body motion with an array of fluidic elastomer actuators. Li T et al. (2017) designed a soft electroactive structure, composed of dielectric elastomer and ionically conductive hydrogel, and this structure can achieve fast moving (0.69 body lengths per second). Rajendran and

Zhang (2021) utilised super-coiled polymers as artificial muscles to drive a novel robotic fish. Liu J et al. (2021) created a continuum robotic dolphin actuated by tendon mechanisms, which has high cruising speed and turning flexibility. For MPF, Low et al. (2011) presented the design of a robotic manta ray (RoMan-III). Rahman et al. (2011) analysed the swimming motion of a squid-like robot with two undulating side fins. In nature, real fish do not exclusively rely on one locomotor mode. They combined multiple locomotor behaviours with improving their aquatic behaviour. Many people have tried this direction in the research of robotic fish. One example is shown in Figure 2(d). Wang W et al. (2010) achieved the preliminary realisation of robotic fish with multiple control surfaces involving tail plus caudal fin, pectoral fins, pelvic fin and dorsal fin. Wu et al. (2015) created a multimodal robotic fish that can execute both BCF and MPF locomotions for enhanced performance in complicated aquatic environments. Zhang S et al. (2016) proposed an integrative biomimetic robotic fish combining the advantages of insect wings and fish fins to achieve high agility underwater.

Although robotic fish has various types, shapes and sizes like natural fish, robotic fish still have many common characteristics overall, including the body outline is diamond-shaped, which gives us great convenience in designing the shape of the robotic fish charging station.

From the development history and classification of robotic fish reviewed above, it can be seen that although it hasn't been a long time since the robotic fish appeared, robotic fish are being studied and optimised by more and more people. In the future, the development of robotic fish will be more mature, its performance will become increasingly amazing, and they will definitely become an excellent main force in ocean exploration and exploitation.

4. Technical issues in the robotic fish docking

In this section, the docking techniques for robotic fish before the charging process are discussed, which includes the methods involved in the navigation process to guide the robotic fish heading towards the docking station in Section 4.1 and the design of the docking station in Section 4.2 so as to provide an overview about the robotic fish docking.

4.1. Robotic fish navigation

In this subsection, the methods of underwater navigation of robotic fish are focused on. For underwater navigation, the existing underwater navigation systems can be divided into three types: acoustic navigation, visual navigation and GPS navigation, which have obvious differences in navigation distance and navigation accuracy. One or multiple navigation methods can be chosen based on the advantages and disadvantages of the three navigation methods in order to achieve the purpose of precise underwater docking of robotic fish.

There are few researches on robotic fish docking so far. Phamduy et al. (2016a) designed an autonomous charging system for a robotic fish. They used the video feedback from an overhead camera to navigate the robotic fish to approach the charging station. Because the camera in Phamduy et al.'s research was mounted on the tank, this navigation method can only be used for small tanks in the laboratory, and was not suitable for robotic fish working in the ocean if their working area and the transparency of the seawater were considered. In contrast, Sun Q et al. (2020) designed the process of using an ultrasonic communication system to complete the underwater docking of a miniature robotic turtle, which is more feasible for underwater docking for robotic fish. They installed an ultrasonic transmitter on the charging platform and an ultrasonic receiver on the left and right sides of the front end of the miniature robotic turtle, which analysed the relative position of the charging platform with respect to the miniature robotic turtle that needed to be charged by the time difference of the ultrasound received by the ultrasonic receiver on the front of the miniature robotic turtle, thereby controlling the movement of the miniature robotic turtle.

As mentioned above, in the future, AUV will gradually be replaced by robotic fish in some areas. Compared to robotic fish, the research on AUV is now very mature. Hence, when the underwater docking of robotic fish is studied, the existing AUV underwater docking technology can be learned from. There have been many studies on the existing AUV underwater docking technology. Wang T et al. (2021) developed an integrated visual navigation and docking algorithm for the miniaturised prototype AUV in the hope of solving the planar-type docking issues by adopting the monocular Simultaneous Localization and Mapping (SLAM) programme. They used image recognition technology to determine the relative position of the charging platform and the AUV, thereby calculating the movement trajectory of the AUV.

However, visual navigation is only suitable for short-distance docking. When the robotic fish is far away from the charging station, visual navigation will fail because of low visibility in the sea. Consequently, in the research of long-distance navigation and docking, the hybrid system of acoustic navigation and visual navigation can effectively solve the problems of low visibility and low docking accuracy. The reason why visual navigation sensors are used at short distances instead of using acoustic navigation sensors is that the acoustic navigation sensors can be very effective from medium to long distances, but it is not so advantageous at short distances when the high precision operation is required for successfully completing the docking process. To achieve a level of performance capable of ensuring the vehicle's safety during the terminal homing, visual navigation sensors are used to provide updates with small uncertainty and high update rates. Hence, when the distance between the robotic fish and the charging station is long, acoustic navigation comes into play, guiding the robotic fish gradually approaching the charging station based on the acoustic data. When the distance between the robotic fish and the charging station can meet the requirement for visibility of the visual navigation, the visual navigation is activated, making the docking more accurate.

Since the multiple sensors based navigation scheme for AUV position estimation proposed by Kalyan and Balasuriya (2004), a lot of researches have focused on the hybrid system of acoustic navigation and visual navigation, whose sketch is shown in Figure 3. Matsuda et al. (2018) conducted the port experiments of the docking using an AUV and a seafloor station through the hybrid system of acoustic and visual positioning methods. The AUV successfully docked with the seafloor station under low visibility and strong ocean currents and charged its battery. Sato et al. (2017) developed

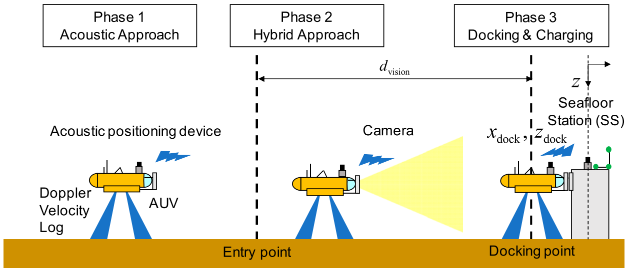


Figure 3. Sketch for Hybrid System of Acoustic Navigation and Visual Navigation (Matsuda et al. 2018). (This figure is available in colour online.)

a subsea charging station for AUV, which automatically docked to the subsea station based on acoustic and visual landmarks. Palomeras et al. (2018) designed two positioning systems in order to realise the autonomous docking of AUVs. The first one implemented only a distance positioning algorithm to approach the docking station, while the second one was based on active optical beacons, which provided high accuracy within a short distance to complete the docking operation.

In terms of long-distance navigation for robotic fish, there is another way, that is to use the Global Positioning System (GPS). However, there is a drawback with this method: when the robotic fish needs to be charged, it needs to float near the water surface to obtain the GPS signal, which causes a lot of trouble in the docking of the robotic fish. Like the acoustic navigation, the accuracy of the GPA navigation system is also not high, and the resolution is basically metres (Odijk et al. 2014). Because of this, it is almost impossible to complete the underwater docking of robotic fish by GPA alone. Therefore, GPS is rarely used for navigation in general docking research of underwater robots (Tan et al. 2006). However, in order to make use of GPS into the navigation of robotic fish, Ryuh et al. (2015) developed a buoy robot floating on the sea surface so that the appropriate location of the school of robotic fish can be recognised, but the distance measurement method between each robotic fish and buoy robot was still acoustic detection.

In this subsection, three different underwater navigation systems have been studied: acoustic navigation, visual navigation and GPS navigation. Based on the advantages and disadvantages of these three navigation methods, it can be concluded that the acoustic navigation is a good solution for medium and long-distance navigation, which can roughly guide the robotic fish to the docking station. Besides, the visual navigation has an obvious advantage in short-distance navigation, which can accurately judge the relative position of the docking station and itself through the robot vision to make the corresponding motion decisions in a timely and effective manner, so as to achieve a smooth and error-free realisation of the underwater docking of robotic fish.

4.2. Design of docking station

The navigation problems in the docking process of robotic fish have been introduced in the previous subsection. In the remainder of this section, the design of the docking station during the robotic fish docking process is studied.

Under normal circumstances, the docking station will be designed and adjusted differently according to the charging method, the surrounding environment (topography, water flow speed, marine life growth) and the shape and size of the robotic fish. There are three possible designs of robotic fish docking stations: unidirectional (funnel-shaped) docking station, omnidirectional docking station and charging platform.

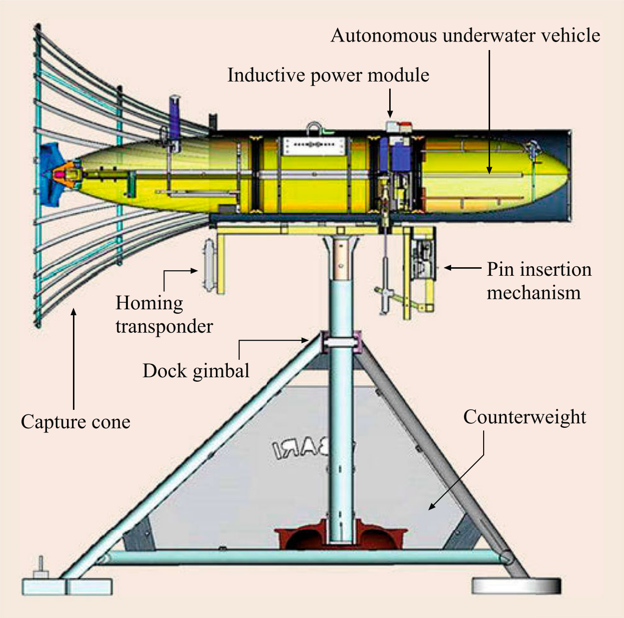


Figure 4. Sketch for Unidirectional Docking Station (Bellingham 2016). (This figure is available in colour online.)

The unidirectional docking station as shown in Figure 4 is the most common configuration usually used for recovering torpedo-shaped robotic fish and typically comprises a funnel/cone-shaped entrance to provide a large cross-section area for the robotic fish capture mechanism. The unidirectional docking station is relatively simple in structure and robotic fish requires less modification for docking (Palomeras et al. 2018). After the robotic fish is docked, energy supplement and data exchange can be carried out in the station without environmental interference in the ocean. However, this docking method requires robotic fish to have good manoeuvrability and motion control capabilities. Because the docking process is greatly affected by anisotropic ocean currents, docking errors are prone to occur. Besides, most of the unidirectional docking stations are tailor-made for torpedo-shaped robotic fish. If the shape of the robotic fish is not torpedo-shaped, it is difficult to use the docking method with a conical guide cover and a cage as the docking target. Compared with the process for the landing of the charging platform as the docking target, the only difference for the unidirectional docking station is that after the robotic fish reaches the minimum accuracy of acoustic navigation sensors, it needs more accurate adjustment for its angle and position in order to enter the chamber of the docking station. When the robotic fish has entered the docking station in its final position, the latching system will play its role, which is developed to prevent the robotic fish from exiting the docking station due to water currents thus allowing it to enter in low power mode once docked. Most underwater docking stations now use unidirectional docking technology. Stokey et al. (2001) developed a design based on a fixed cone leading into a tube (effectively a horizontal funnel), which provided a protective garage for the vehicle. Yan Z et al. (2016) proposed a novel underwater contactless power transmission (CPT) system based on the arc electromagnetic coupler (EC) with the unidirectional docking station. Matsuda et al. (2019) designed a resident autonomous underwater vehicle system for monitoring an underwater infrastructure with a funnel-shaped docking station. Ryuh et al. (2015) utilised the buoy robot, which can not only serve as the navigation relay station but also provide the electric power for a school of robotic fish.

The omnidirectional docking station as shown in Figure 5 is usually designed as a vertical structure consisting of a rigid rod or cable under tension, enabling the vehicle to connect itself to the rod or cable using a latch device installed at the front of the vehicle. Rod arrangements are usually used with fixed docks, while tension cable arrangements are usually used with towing docks (Yazdani et al. 2020). The advantages of the omnidirectional docking station are: robotic fish can achieve all-round docking with the docking target in the water, the interference from the marine environment is relatively small, and the docking reliability is high. However, for a certain type of robotic fish, the use of the omnidirectional docking station is restricted, because the lock on this structure requires the implementation of complex mechanical devices on the head of the robotic fish, so it is difficult to install a forward-looking sonar and camera, particularly in smaller vehicles (Bellingham 2016). Also,

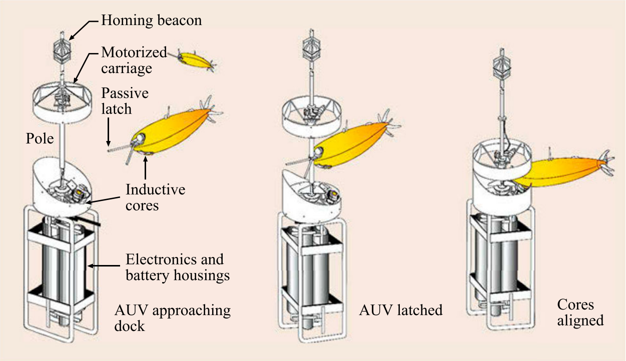


Figure 5. Sketch for Omnidirectional Docking Station (Bellingham 2016). (This figure is available in colour online.)

the structure of the docking base station is relatively more complicated than other two docking methods. Few people conduct research on the omnidirectional docking station. Singh et al. (2001) presented a system based upon an acoustic ultrashort baseline system that allows the AUV to approach the dock from any direction based on the omnidirectional docking station.

Charging platform docking is much like a carrier-based aircraft taking off and landing on an aircraft carrier as shown in Figure 6. This docking method greatly improves the probability of successful docking because the robotic fish can land on the charging platform from any direction and any height, and as long as the robotic fish is parked on the charging platform, and then minor adjustments are made, the charging process can be carried out. Kawasaki et al. (2003) designed a docking base for battery charging of Marine Bird-a kind of autonomous underwater vehicle. Yang C et al. (2019) proposed an omnidirectional planar AUV charging platform providing an AUV with stable charging performance regardless of its position and direction. Wang T et al. (2021) developed an omnidirectional and positioning-tolerant planar type AUV docking and charging platform, which had no constraints on AUV structures.

In addition, the design of the docking station is far more than these three common solutions. Many very characteristic docking stations have been invented. Phamduy et al. (2016a) designed a robotic fish docking station with a claw shape shown in Figure 7, which was composed of two claws. When the robotic fish wanted to dock, the claws farther from the robotic fish closed first, and then the robotic fish slowly approached the docking station until the front end of the robotic fish fitted with the closed claw. Then the claws closer to the robotic fish closed and ‘grabbed’ the robotic fish’s tail, which can make the robotic fish more stable when charging. After the robotic fish was fully charged, both claws were opened at the same time, and the robotic fish returned to the ocean to work.

In this subsection, four design schemes for underwater docking stations: the unidirectional docking station, the omnidirectional docking stations, the charging platform and the claw-shaped docking station have been introduced. In the following, these solutions are compared to find a docking station that is more suitable for robotic fish to complete underwater docking.

Figure 6. Sketch for Charging Platform Docking Method (Wang T et al. 2021). (This figure is available in colour online.)

First, the shape and size of the robotic fish should be considered. Unidirectional docking stations and claw-shaped docking stations can only be used for robotic fish of specific shape and size. Because for unidirectional docking stations, the cross-sectional radius of the robotic fish should not be too large, too large will cause the robotic fish to be unable to enter; the cross-sectional radius of the robotic fish should also not be too small, which will cause the energy transmission efficiency to be very low when using wireless charging. The claws in the claw-shaped docking stations also need to be tailored for robotic fish based on their shape and size. Because the claws here must hold the robotic fish steadily to facilitate subsequent charging operations. Different from unidirectional docking stations and claw-shaped docking stations, omnidirectional docking stations and charging platform do not have very high requirements on the shape and size of robotic fish. Because robotic fish hover above these two docking stations so that there is almost no contact. As mentioned above, the omnidirectional docking stations require a special docking rod installed on the front of the robotic fish, which is not friendly to the design of the robotic fish. Therefore, the only docking station that can really ignore the shape and size of the robotic fish is the charging platform.

Secondly, from the perspective of the wear and tear of the docking stations and the robotic fish, the claws in the claw-shaped docking stations need to be in contact with the robotic fish. Therefore, during the docking process, the wear and tear of the robotic fish and claws will be relatively serious. However, this kind of problem will not happen on unidirectional docking stations and charging platforms because there is almost non-contact between the robotic fish and the docking stations of these two docking methods.

In addition, from the perspective of the feasibility and convenience of docking, the charging platform can allow robotic fish to dock on the charging platform from different directions, which greatly improves the convenience and feasibility of docking. On the contrary, robotic fish can only enter from the opening of the unidirectional docking stations. Consequently, before the docking starts, the robotic fish needs to adjust the position and direction of the relative docking stations to meet the requirements of being able to enter the docking stations smoothly.

Finally, since the robotic fish is susceptible to drifting due to the fluctuation of the water flow in the ocean during the underwater charging process, which affects the feasibility and safety of charging, the stability of these docking methods needs to be considered. Obviously, the charging platform is the most susceptible to the impact of the current in the ocean because the robotic fish is hovering above the charging platform. If this docking method is adopted, the position shift of the robotic fish needs to be considered during the charging process. Another docking method-unidirectional docking stations-can effectively reduce the impact of ocean currents on robotic fish charging because this charging method requires robotic fish to enter a container. Consequently, in general, unidirectional docking stations have higher stability when charging robotic fish.

From the above comparison, it can be concluded that when the shape and size of the robotic fish used for ocean exploration are uniform, using unidirectional docking stations is a good choice, because it can ensure the stability of the charging process. However, when the shape and size of the robotic fish are different, the charging platform can be utilised to solve this problem, because it not only has a high tolerance for shape and size, but also has a high degree of freedom in the docking process.

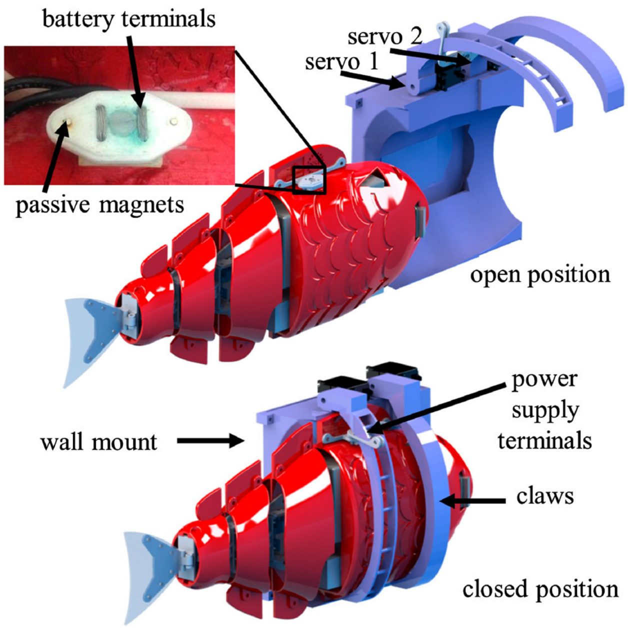


Figure 7. Sketch for Claw-Shaped Docking Station (Phamduy et al. 2016b). (This figure is available in colour online.)

5. Technical issues in the robotic fish charging

In this section, a very important focus of this paper-the underwater charging technology of robotic fish is discussed. Based on the design of the docking station mentioned in Section 4.2, the corresponding charging methods of different docking stations to complete the underwater charging of the robotic fish are explored.

Generally speaking, charging with plugs is the most common way of charging in the daily lives, and almost all kinds of electrical appliances are charged with plugs. However, it is extremely difficult to use a plug to charge underwater. This is because the leakage of charging in seawater needs to be considered. Seawater conducts electricity more easily than ordinary freshwater, which will cause a short circuit between the charging equipment and the equipment being charged, and in serious cases, it will cause equipment failure. Therefore, charging using plugs underwater requires a special plug design to avoid short circuits. Wet-pluggable connector is one of the solutions. Wet-pluggable connectors use pressure to squeeze seawater out of the charging port to achieve the purpose of sealing (Tender et al. 2008). Although the traditionally used wet-pluggable connector technology is relatively mature, it also has inherent shortcomings. The ocean is full of seawater with good conductivity, and the wet-pluggable connector is directly electrically connected, and there is always a safety hazard that seawater leaks and causes short-circuiting of metal contact points. Squeeze sealing is the main method for the wet-pluggable connector to prevent seawater from penetrating into the metal conductor, but it requires more than 100 N of insertion and extraction force (Sigler et al. 2015). It is difficult to complete this operation by the electromechanical equipment alone and it must be done with the help of a Remotely Operated Vehicle (ROV) and other equipment so that the charging process can be realised, which not only greatly reduces the autonomy and flexibility of deep-sea electromechanical equipment, especially robotic fish, but also increases operating costs. In addition, frequent squeezing and plugging operations will inevitably lead to physical wear and tear on the interface of the wet-pluggable connector, which will greatly reduce the service life of the wet-pluggable connector. Because the wet-pluggable connector has many shortcomings and troubles, few researchers will apply it to the underwater charging of robotic fish. In the reference list, only the aforementioned claw-shaped docking station uses a wet-pluggable connector (Phamduy et al. 2016a). When both claws are closed, the robotic fish is immobilised. The wet-pluggable connector starts to work. It inserts the plug into the charging port of the robotic fish to start charging. When the charging is complete, the wet-pluggable connector is unplugged from the charging port of the robotic fish. Because of the unique design of this docking station, the robotic fish can be fully fixed, so that the wet-pluggable connector can be connected to the robotic fish smoothly. However, wet-pluggable connectors are difficult to apply to other docking stations, because they hardly fix the robotic fish completely.

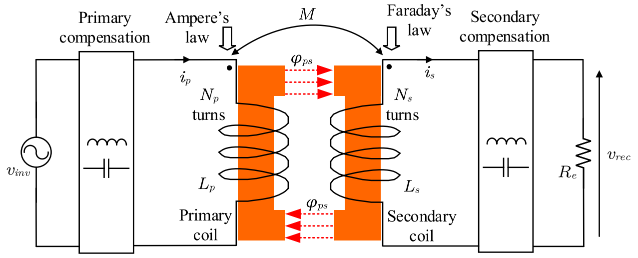


Figure 8. Sketch for Inductively Coupled Power Transfer (ICPT) System (Bagchi 2020). (This figure is available in colour online.)

Another charging method is called Inductively Coupled Power Transfer (ICPT) as shown in Figure 8, which converts electrical energy into electromagnetic field energy through the electromagnetic coupling between the primary and secondary couplers to achieve non-contact power transfer. With the development of power electronics technology and the progress of power devices, ICPT technology has been widely used in power transmission in various applications, and has shown unique advantages under some extreme environments and special conditions. In underwater applications, ICPT technology has no direct electrical contact during transmission, avoiding potential safety hazards such as leakage, short circuit and electric shock. Moreover, the ICPT technology does not need to be squeezed and sealed to achieve the insulation effect, and can simplify the plug-in operation through a reasonable mechanical structure design and reduce the wear of the interface. In addition, compared with the traditional wet plug interface, the manufacturing cost and use cost of ICPT also have greater advantages. Boys et al. (2002) was the first team to study ICPT technology. They developed a 30 kW non-contact power passenger electric transport vehicle in Rotorua National Geothermal Park in New Zealand and the maximum gap between the receiving coil on the electric vehicle and the transmitting coil buried on the ground can reach 5 cm when charging. After decades of development, the application of ICPT in underwater charging technology has become more and more mature. Yang C et al. (2020) used the simple but effective inductive power transmission (IPT) system to realise underwater wireless charging for an AUV docking system. Lin M et al. (2017) proposed a pair of coaxial and coreless coil structure for battery charging of the AUV, whose efficiency can vary from 75% to 91% with a total efficiency of 63-77% during the entire charging period. Rosu et al. (2019) developed an underwater inductive charging system of autonomous underwater vehicles with the scope of extending their autonomy, whose geometry was based on truncated coils, adapted to the hydrodynamic geometry of the AUV. Kan et al. (2017) modelled a three-phase wireless charging system that could be used in a field-deployable charging station capable of rapid, efficient and convenient AUV recharging which is able to transfer 1.0 kW with a DC-DC efficiency of 92.41% at

465 kHz. Kan et al. (2018) also proposed a rotation-resilient wireless underwater charging system for AUVs, which can transfer 745 W in a DC-DC form with the efficiency of 86.19%. Liu Z et al. (2021) studied multi-objective design method of underwater wireless power transfer (UWPT) system for autonomous underwater vehicles based on the cooperative design of compensation network and a DC-DC converter, considering seawater eddy current loss. Ryuh et al. (2015) employed the buoy robot so that the robotic fish can enter it for wireless charging based on ICPT. Orekan et al. (2018) presented an undersea wireless power transfer system whose peak efficiency can reach 85%. Shi et al. (2014) designed an underwater ICPT system in order to charge the AUV, for which the output power can be up to 45 W and the efficiency can be up to 84%. Cheng et al. (2014) demonstrated a novel underwater loosely coupled transformer, which can deliver 10 kW with the maximal transmission efficiency of 91%. Cai et al. (2021) built an ICPT system with the advantages of lightweight in receiver and fit-to-surface and it can transfer 1 kW at a DC-DC efficiency of 95.1%.

In addition to these two common charging methods, there are also some special charging methods. Fan and Ishibashi (2015) proposed a system to help guide the underwater vehicle to dock, whose main components of the system were light emitting diodes (LEDs) on the docking station that act as both a visual beacon and energy source, a vision system on the AUV to detect the docking station, and photovoltaic (PV) panels onboard the AUV to receive energy from the docking station.

In all these studies, ICPT wireless charging technology has shown excellent convenience and flexibility, and the existing ICPT technology can basically achieve energy transmission efficiency of 90%, which provides us with a good solution to the study of using MRE to complete underwater charging of robotic fish.

6. A preliminary design study for docking and charging

In this section, all the technologies discussed above are combined to propose a preliminary design for docking and charging based on our review work and this might be helpful for some readers to continue their research based on our theoretical study.

First, the design of the charging end of the system that uses MRE to charge robotic fish underwater is explored. In Section 2.2, it has been mentioned that most MRE conversion stations can be simplified into a model: an energy conversion device (wave energy converter or solar panels) uses buoys to float on the sea and is anchored by an anchor. The phenomenon of magnetic induction generates electrical energy from the MRE. The generated electrical energy is stored in a storage battery.

Secondly, the underwater docking technology of robotic fish is analysed. In Section 4.1, it can be learnt that the hybrid system of acoustic navigation and visual navigation is the best choice for robotic fish navigation. This not only allows the robotic fish to use the acoustic navigation to roughly return to the docking station for the medium and long distances, but also to successfully dock with the robotic fish using the visual navigation at short distances. In addition, for the choice of docking station in Section 4.2, the type of docking station can be utilised according to the characteristics of robotic fish. If similar types of robotic fish are applied, the unidirectional docking station can be utilised, because this can make the robotic fish more stable when charging. If the robotic fish are very different in shape and size, a docking station in the form of charging platform is utilised, because it can not only meet the needs of successful docking of different types of robotic fish at the same time, but also allow robotic fish to dock from different directions.

Finally, regarding the charging technology, ICPT is the optimal solution, because it not only simplifies the charging process, but also has very wonderful energy transmission efficiency.

In summary, the proposed system that uses MRE to complete underwater charging for robotic fish can be designed in this way. The MRE conversion device collects MRE on the sea surface, converts it into electrical energy and stores it in a battery for robotic fish. When the robotic fish needs to be charged, the robotic fish first judges the location of the docking station closest to itself using the acoustic navigation, and if the distance is long, continues to use the acoustic navigation to navigate the robotic fish to a place closer to the docking station, and then the visual navigation is activated to complete the precise docking of robotic fish. When the docking is completed, the ICPT system starts to work to charge the robotic fish. After the charging is completed, the robotic fish leaves the docking station to continue ocean exploration and monitoring. It is our wish that someone may implement the design physically to test its effectiveness.

7. Summary and conclusions

In this paper, a comprehensive review of underwater automatic charging methods and systems for robotic fish based on the existing marine renewable energy conversion technology has been carried out, including marine renewable energy, robotic fish, underwater docking techniques of robotic fish, underwater charging platform of robotic fish, and charging methods of robotic fish. Based on the review and a comparative analysis, a novel system design for underwater charging for a school of robotic fish through renewable energy has been proposed. The authors will continue to seek funding for physical implementation and also welcome interested readers to test its effectiveness. From our own judgment, the design of using MRE to complete underwater charging for robotic fish is feasible by just using the existing technology. The proposed design scheme can not only make good use of MRE, but also greatly simplify the marine deployment of swarms of robotic fish, expand the working range of robotic fish, and extend the working cycle of robotic fish, which has laid a solid foundation for the large-scale use of robotic fish for ocean exploration and cruise in the future.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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