Cui *et al.*
Intelligent Marine Technology and Systems (2023) 1:7
https://doi.org/10.1007/s44295-023-00010-3

Intelligent Marine Technology and Systems

REVIEW

Open Access

Review of research and control technology of underwater bionic robots

Zhongao Cui[1†], Liao Li[1†], Yuhang Wang[1], Zhiwei Zhong[1] and Junyang Li[1*]

Abstract

As marine resources continue to be exploited, the remarkable locomotion and coordination of fish provide an excellent source of inspiration for scientists and engineers to design and control the next -generation autonomous underwater vehicles within a bionic framework. Underwater biomimetic robots combine bionics and robot technology, and their biological characteristics offer a lot of convenience for the robot so that it can obtain better performance in adaptability and robustness. Recently, with the combination of bionics, mechanics, electronics, materials science, and automation, there has been great progress in developing underwater bionic robots with different structure types and energy supply modes. This paper summarizes the research status of underwater robots, focuses on the research status of underwater bionic robots with different materials, types and motion modes, and introduces the propulsion mechanism of underwater robots with different structures and the control methods adopted in the propulsion process. Finally, the broad application prospect and market potential of underwater biomimetic robot are introduced.

Keywords Underwater bionic robot, Propulsion mechanism, Control strategies, Application scenarios

1 Introduction

A bionic underwater robot, as the name suggests, is a new type of robot that imitates the propulsion mechanism and body structure of fish or other marine creatures living underwater using electromechanical components and intelligent materials (such as memory alloy materials, mixed materials, and rigid materials), which can adapt to different underwater environments and realize underwater propulsion (Chu et al. 2012). It has the characteristics of high efficiency, high mobility, and low noise (Chen et al. 2021a). For a long time, scholars have been committed to studying marine biological propulsion models and bionic underwater robots. Underwater vehicles can be classified into two groups based on their structural design: cabled underwater vehicles, commonly known as remotely operated vehicles (ROVs), and cableless underwater robots, traditionally known as autonomous underwater vehicles (AUVs) (Wynn et al. 2014). Moreover, they can be categorized by use into underwater investigation robots (observation, measurement, test material collection, etc.) and underwater operation robots (underwater welding, pipe twisting, underwater construction, underwater cutting, etc.) (Vu et al. 2018).

At present, most underwater robots are frame-based, similar to the rotating elongated body of a submarine. With the continuous development of bionic technology, the bionic fish shape and control modes of underwater robots will also evolve (Xie et al. 2021). In this review, different control system algorithms are described, such as those developed for individual or cluster control of underwater robots (Khalaji and Zahedifar 2020). Underwater robots work in unknown and challenging marine environments. Complex marine environments, such as wind, waves, currents, and water pressure, severely interfere with robot motion and control, making communication and navigation of underwater robots very difficult. Thus, the development potential of underwater robots

†Zhongao Cui and Liao Li contributed equally to this work.

*Correspondence:
Junyang Li
junyangli3-c@my.cityu.edu.hk
[1] College of Information Science and Engineering, Ocean University of China, Qingdao 266100, China

still needs to be continuously explored. In this paper, various underwater robots are reviewed and introduced from manufacturing materials, structural design, drive mechanism, and control strategy.

1.1 Shape memory alloy material

Shape memory alloys (SMAs) are solid, smart materials driven by current silently. The principle of operation is that when heated from low-temperature martensite to high-temperature austenite, SMA returns to the predetermined shape and generates activation, a process known as the reversed-phase transition (Yang et al. 2023). When cooled from austenite to martensite, SMA experiences a martensitic phase transition and returns to its initial state under bias stress (Hu et al. 2023). Previous works reported that the bionic starfish robot and the bionic manta ray robot fish were both powered by SMA.

The jellyfish robot, or Robojelly, developed by Virginia Tech, is driven by a bionic shape memory alloy composite actuator modeled after a jellyfish. With a body made of RTV silicone with a total mass of 242 g and a bell-shaped diameter of 164 mm, Robojelly can generate enough thrust to propel itself in static water conditions (Villanueva et al. 2011) (Fig. 1a). Harbin Engineering University developed an underwater jellyfish microrobot prototype model based on SMA and ionic conductive polymer film (ICPF) as actuators to achieve swimming movement, with an overall size of microrobot of about 75 mm long, 55 mm in diameter, and 6.5 g weight. This tiny jellyfish-like robot has four tentacles (Fig. 1b). Each mechanism consists of a restraint mechanism and an ICPF actuator, and each tentacle can work with an SMA driver to increase its range of motion and provide greater propulsion. The energized SMA shrinks the internal volume of the microrobot so that the water or other water-containing medium inside the microrobot is driven backward, thus forming a propulsion force (Yang et al. 2007). Another jet-propelled jellyfish bionic robot, MPA-O, developed by Harbin Engineering University, is made of SMA material. The length of the moving direction is 46.1 mm, and the section diameter is 36.3 mm. At an operating frequency of 0.6 Hz, the robot has a maximum speed of 6 mm/s (Guo et al. 2007) (Fig. 1c).

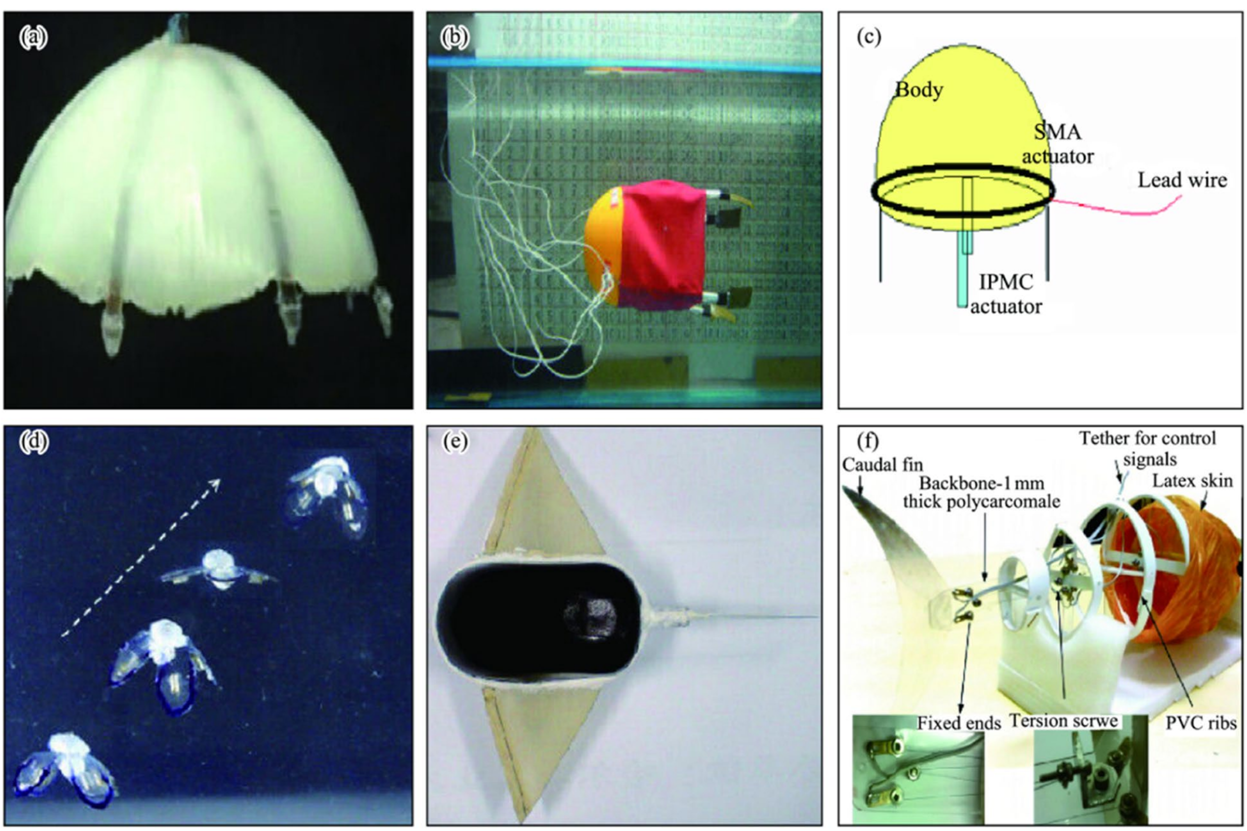

Fig. 1 SMA material underwater bionic robot. **a** Jellyfish robot (Villanueva et al. 2011); **b** Jellyfish-like microrobot (Yang et al. 2007); **c** Jellyfish-like micro robot that achieves MPA-O swimming mode using a hybrid actuator (Guo et al. 2007); **d** Structure of the jellyfish-like robot (Ko et al. 2012); **e** Microrobot manta ray (Wang et al. 2009); **f** Fish skeleton structure including a latex-based skin for water protection (Rossi et al. 2011)

The miniature jellyfish swimming robot, powered by the SMA system developed by Chonnam National University, has four flexible fins, each equipped with a permanent magnet for electromagnetic drive, and the body of the robot has a length of 17 mm and a thickness of 0.5 mm. The SMA driver can generate a uniform magnetic field in the desired direction in 3D space, which can bend the fins of the jellyfish-like microrobot. Thus, the cyclic changes in the uniform magnetic field will synchronize the fluctuations of the fins and generate a propulsive force for the robot in the desired direction (Ko et al. 2012) (Fig. 1d). A miniature bionic manta ray robotic fish with a triangular pectoral fin driven by SMA, developed by the Harbin Institute of Technology, is based on the simplified pectoral fin model described in the joint. Each consists of a bionic fin on the leading edge and a latex film (0.2 mm thick) that forms the surface of the fin. The front part of the tail is attached to the body and is a flexible fin that can adjust the course (Wang et al. 2009) (Fig. 1e). The SMA is used as a continuous backbone for curved fish, and the University of Madrid utilized six SMA-based actuators to make the skeleton of the robotic fish. Their length is 1/3 of their body length (8.5 cm, excluding the tail fins and head). They are positioned in pairs parallel to the body so that antagonistic motion can enable the robotic fish to resist higher water pressure (Rossi et al. 2011) (Fig. 1f).

Jellyfish robots developed at Kagawa University achieved flutter-like motion with SMA-based actuators and positive spring elements (Najem et al. 2012). The robot was 63 mm long, 35 mm wide, and 18 mm high, the same size as the manta ray robot previously developed by the laboratory, which was constructed with SMA wires embedded in an elastic substrate (Xie et al. 2018). The jellyfish robot's fluctuating motion is generated by 10 SMA actuators (5 on each side) with a maximum speed of 40 mm/s at 3.125 Hz, and the Department of Health Sciences and Technology of ETH Zurich (Vogel 2012) developed another jellyfish-like robot with jet propulsion via an SMA-based actuator. The drive is called bionic shape memory alloy composite (BISMAC). BISMAC is assembled from a steel spring and SMA wire embedded in a silicone precision connection (Ma et al. 2019) and has a length of 110 mm and thickness of 0.1 mm, while the bell has diameters of 134 and 82 mm. The robot is 242 mm long, 225 mm wide, and 52 mm high. Because its main component is silicone, it has greater hardness, strong compressive performance, and a speed of 35 mm/s. Traditional robots are machined from rigid materials, which often limits their ability to deform and adapt their shape to the external environment. Although these rigid robots have the advantages of large output force, high precision, and strong controllability, they often lack the multifunctional characteristics of natural organisms. Flexible robots comprising SMA materials can achieve elastic deformation and pass through narrow spaces without causing internal damage (Hu et al. 2019).

1.2 Ionic polymer–metal composite

Biomimetic artificial muscle material is a new type of intelligent material developed rapidly in the 1990s, constantly setting off a global research upsurge and has important application value in the aerospace, biomimetic robot, and biomedical engineering fields. Ionic polymer-metal composites (IPMC), as electrochemical actuators, are typical biomimetic artificial muscle materials (Şafak and Adams 2002) with a sandwich structure comprising two layers of electrodes and ionic polymers. Under the electric field, electrical and mechanical energy can be converted by the reversible dissociation process of ions at the electrode interface. IPMC material has the advantages of fast response, large drive displacement, and low drive voltage. However, it can only be used in wet environments and has huge limited applications in amphibious bionic robots (Cao et al. 2022).

IPMC is widely used in the manufacture of body or caudal-fin (BDF) swimming robots, and the fish-like robot developed by the New York Institute of Technology is designed with IPMC materials, which mimics the general swimming movement of a fish, protecting itself with its tail fin (Marras and Porfiri 2012). In 2010, Michigan State University developed a wireless bionic robotic fish that also successfully demonstrated the swimming mode of the BCF using a robot based on IPMC as the driving material, which had four different types of fins mounted on its tail to optimize the relationship between robot speed and fin shape (Brown and Clark 2010). The University of Science and Technology of China employed the IPMC brake as the tail fin of the robot fish for propulsion, which mainly comprises two servo motors, namely, angle rotating block pairs and brakes, and the main body is arranged symmetrically. The experiment confirms that the robot fish with the two degrees of freedom caudal-fin propulsion mechanism can realize various basic swimming movements by using a caudal fin (Zhou et al. 2017) (Fig. 2a). The University of Nevada studied a biomimetic jellyfish robot powered by an IPMC placed inside a silicone dome. Because the selected jellyfish shell elastomer material is soft enough, the IMP can be easily driven without hindrance, and the robot can increase thrust production by approximately 1300% compared to a normal jellyfish (Trabia et al. 2016) (Fig. 2b).

The University of Virginia developed a biomimetic robot that mimics a manta ray's pectoral fin, which partially comprises a PDMS (polydimethylsiloxane) membrane using four IPMCs (0.28 mm thick)

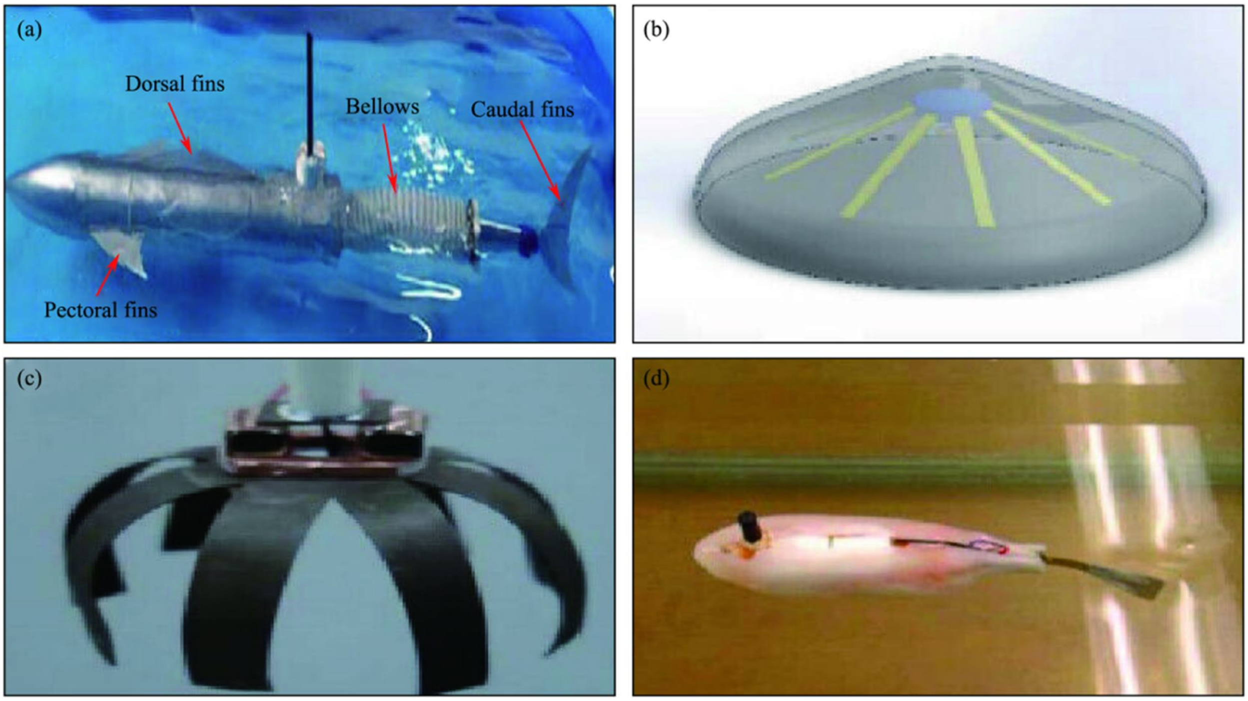

Fig. 2 IPMC material robot fish. **a** Prototype of the robotic fish (Zhou et al. 2017); **b** Robot jellyfish prototype (Trabia et al. 2016); **c** IPMC material jellyfish robot (Yeom and Oh 2008); **d** Robot fish propelled by IPMC (Hu and Zhou 2009)

(Sankaranarayanan et al. 2008). Jeonnam National University utilized IPMC actuators to build and evaluate biomimetic jellyfish robots. The existing IPMC actuators limit their application fields due to their flat shape, which is a severe defect of this actuator material. To overcome the disadvantages of planar IPMC actuators, a curved IPMC actuator with predetermined initial deformation is developed. The expected initial deformation is acquired by heat treatment. The bionic input signal is generated by imitating the real movement of jellyfish (Yeom and Oh 2008) (Fig. 2c). The experiment confirms that the jellyfish robot can move normally. IPMC is an important electroactive polymer (artificial muscle) with built-in drive and sensing capabilities. The robotic fish developed by the Intelligent Microsystems Laboratory at Michigan State University comprises IMPC material. Its motion mechanism includes the following: IPMC usually includes a thin ion exchange membrane, which is chemically plated on two surfaces with precious metals as electrodes. Application of voltage to the IPMC leads to the transport of hydrated cations and water molecules within the membrane and the associated electrostatic interactions to result in bending motion, leading to a driving effect (Hu and Zhou 2009) (Fig. 2d). The artificial muscles of biomimetic robots' balance drive the performance, power-to-weight ratio, and muscle form factors. As such, they are ideally suited as biomimetic actuators for various robotic applications. In the past decade, research and application of robotic artificial muscles have been developed (Wynn et al. 2014). More fundamental research is required regarding how artificial muscles can be manufactured, modeled, controlled, and engineered to acquire fish-like muscle properties and achieve muscle-like behavior.

1.3 Piezoelectric composite ceramics

A group of researchers from the Artificial Muscle Research Center at Konkuk University in South Korea developed a bionic fish robot that utilizes its tail fin to drive the swimming motion of BCF (Pham et al. 2023) and used a lightweight piezoelectric composite ceramic (PZT), a single crystal piezoelectric ceramic encased in glass/epoxy and carbon/epoxy resins, as the actuator material. The robot uses a crank, rack, and pinion structure (the size of the robot is increased by 400 mm due to the need for an additional device to achieve the movement). The robot has a maximum speed of 25.16 mm/s at an operating voltage of 300 vpp and an operating frequency of 0.9 Hz.

The miniature underwater mobile robot developed by Professor Toshio Fukuda of Nagoya University in Japan contains piezoelectric ceramics to drive the oscillation of two symmetrical legs to realize its movement. The two legs of the robot are equipped with a pair of symmetrical fins at a certain angle. The symmetrical structural design can offset the lateral force and strengthen the forward momentum. A 250-fold elastic hinge amplification mechanism is designed to amplify the PZT. The robot is 320 mm long and 190 mm wide, and the motion speed is 21.6–32.5 m/s. In 2009, the Marine Science Center of Northeastern University in the United States developed a robot fish with wave propulsion using PZT materials and chain rod structure (Zhou et al. 2008). Through lateral body fluctuations, the robotic eel drives itself through the water column and controls its floating depth. In 2008, DRAPER Lab launched VCUUV (Vorticity Control Unmanned Underwater Vehicle), a piezoelectric ceramic-driven robot fish designed after tuna (Suk and Hwan 2014). It is about 2.4 m long and weighs 300 lbs. Its maximum swing frequency is 1.5 Hz, with a maximum swimming speed of 1.25 m/s at 1 Hz. The goal of the laboratory is to develop an autonomous underwater vehicle using eddy current-controlled propulsion and show that PZT materials have good drag reduction characteristics, excellent maneuverability, depth-holding ability, and higher acceleration and deceleration ability through free swimming. Harbin Engineering University (Yue et al. 2015) developed a water microrobot with a PZT drive; the main feature of this drive is that it is a polymer material actuator only in water or wet environment work. The robot, which can be turned forward, left, or right, has a pair of driving wings driven by a pulse voltage to generate propulsion. PZT material can realize the continuous fluctuation deformation of the fluctuating fins of bionic fish, which makes it compact in structure, light in weight, and high in efficiency. This kind of robot has broad application prospects and value in microtubule detection and biomedicine.

1.4 Mixed materials

The underwater environment is complex, so the material requirements of the underwater bionic robot are very strict. Currently, polymer-metal composite materials are widely employed, combining the advantages of both the polymer and the metal. Polymers can withstand a certain degree of deformation in most environments. Both materials can make good adjustments to the impact of the external environment, with the polymer being lighter and the metal material being harder (Zheng et al. 2020). The robot fish developed by Shandong University of Technology is made of a resin-mixed material and a rigid motor, with four main parts: two laminated tail fins, a rigid fish body with a permanent magnet at the tail, a miniature battery, and a controller. During the driving process, electrical energy is converted into mechanical energy of the tail fin, producing the swimming motion of the robotic fish (Yan et al. 2021) (Fig. 3a). Kagawa University has developed a medusa-like underwater bionic microrobot based on SMA and artificial muscles. It moves like a jellyfish, floats and sinks, and has two pectoral fins to achieve swimming motion (Shi et al. 2010) (Fig. 3b). The mollusk developed by Zhejiang University includes a steering electronic server, a steering tail, and two SMA flapping wings. Two dielectric elastomer

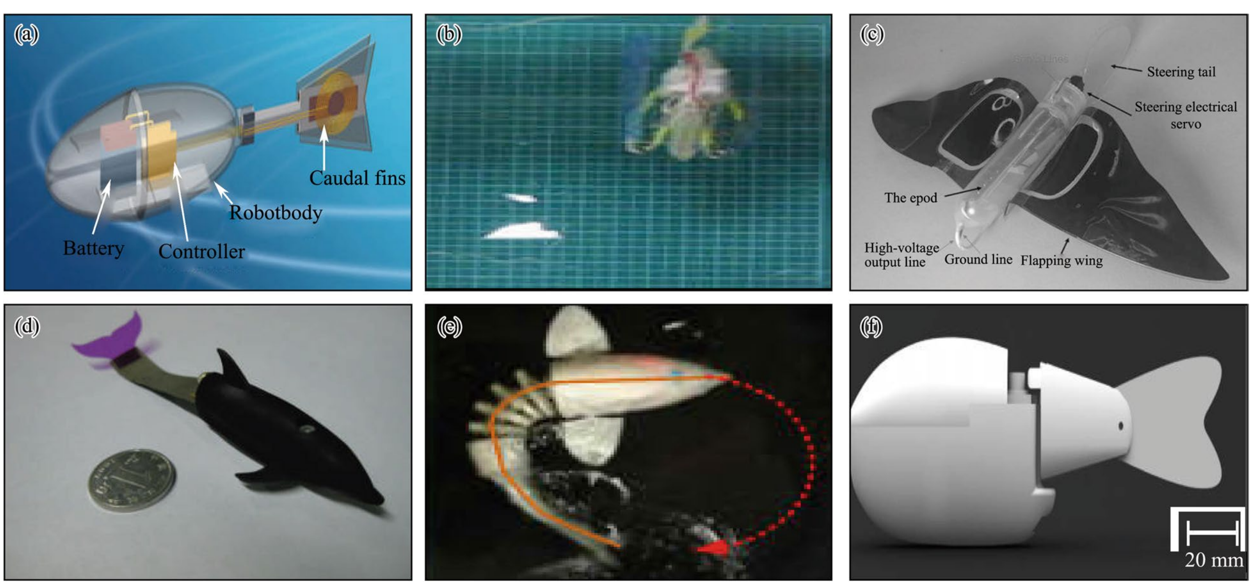

Fig. 3 Mixed-material robot. **a** Composite robotic fish structure (Yan et al. 2021); **b** Prototype jellyfish-like biomimetic underwater microrobot (Shi et al. 2010); **c** Mechanism composition of the soft robotic fish (Zhang et al. 2021); **d** Dolphin robot (Shen et al. 2013); **e** Composite robotic fish (Xie et al. 2020); **f** Illustration of the robotic fish (Marras and Porfiri 2012)

(DE) membranes are clamped onto the electrodes to form an artificial muscle. Precut frames and precut rebar are glued to each side of the muscle. The purpose of the insulation board is to prevent the feed pipe to make contact with the support frame. The flexible wavy fins provide power when the wings are in the flapping, stretching, or actuating state. When AC voltage is applied, the wing changes back and forth between the former state and the driven state, providing forward force (Zhang et al. 2021) (Fig. 3c).

DE, which is widely used in robot drives, has good softness, and its outstanding advantages are that the relative adjustment rate after shape change is fast, the response is quite rapid, the energy consumption is less, and the mechanical and electrical conversion efficiencies are high. The dielectric elastic material-driven robot developed by Kagawa University is a jet propulsion robot simulating a pike (Bal et al. 2019). The driver is composed of SMA, ICPF, and rubber materials. The length of the motion direction is 46.1 mm, the diameter of the section is 36.3 mm, and the maximum speed of the robot is 6 mm/s. The dolphin robot developed by Beihang University consists of three parts: (1) a rigid plastic shell that acts as a body, (2) IPMC stripes that act as muscles, and (3) a plastic sheet that mimics a tail fin. The shell is designed based on the proportions of the dolphin's streamlined body, made of nylon plastic, using a 3D printer, and covered with a black matte resin varnish, leading to a smooth surface. The IPMC is attached to the body by two small rectangular conductive copper plates, which act as clamps, with a flexible fin attached to the end of the IPMC, which is designed based on the shape of a natural dolphin fin. The robot can jump and swim freely like a dolphin (Shen et al. 2013) (Fig. 3d). The bionic robotic fish developed by the Chinese University of Hong Kong includes a rigid head, a wired-driven active body, and a flexible tail. A pair of SMA spring plates with the same stiffness pass through an active body comprising multiple connecting rods, which are like the backbone of a real fish, and then distribute a pair of wires along the spring plate to drive the moving body. The robotic fish tail is a flexible tail made of silicone and carbon fiber reinforced material that allows the robotic fish to swim in multiple modes, such as cruising, turning, rising, and descending (Xie et al. 2020) (Fig. 3e). The robotic fish designed by the New York University consists of a rigid acrylonitrile butadiene styrene (ABS) plastic body shell and a tail consisting of rigid ABS elements and flexible polyester tail fins. The robot fish uses a waterproof servo motor to control the tail, and a flexible tail fin allows the tail to bend and undulate to mimic the swimming of a live fish. The tail beat frequency and amplitude of the robot are controlled by an external microcontroller. The signals driven by the servo motor generate the periodic sinusoidal movement of the flexible polyester tail fin to mimic the movement of fish (Marras and Porfiri 2012) (Fig. 3f).

2 Underwater robot control system classification

At present, the commonly used motion control methods of underwater biomimetic robots are model-based control methods, sine controllers, and central mode generator (CPG)-based methods. As the structural components of marine biomimetic robots usually include power modules, sensors, chips, and driving components, the behavior of the bionic robot is controlled by the predefined program or the command controller (the power supply of the controller is mainly provided by traditional lithium batteries) (Chen et al. 2021b). Depth adjustment of the robot in water is controlled by the controller and is mainly completed by the buoyancy unit. Thus, control can also be divided into rigid motor control and soft drive control.

2.1 Model control method

The model control method is performed by analyzing the dynamics and kinematics of the robot and then establishing a complex mathematical model. The mathematical model can accurately calculate the next movement of the robot to achieve the effect of precise control. However, due to the complex and changeable underwater environment, accurately modeling the robot is very difficult. Even if it can be accurately modeled, its control mode is very complex. In 2014, Inner Mongolia University of Technology (Li et al. 2014b) developed a set of integrated and efficient driving devices that can control the swing of the fishtail to achieve different amplitudes, different frequencies, and different central positions and realize the functions of acceleration, deceleration, and steering of the released robot fish. Based on elastic plate deformation theory, the design size and motion input of the elastic plate are inversely solved according to the motion function of the actual fish, which makes the deformation motion of the elastic plate highly fit the fishtail swing in reality. The 3D modeling and fluid simulation of the fish body were performed, and the geometric size and motion mode of the prototype were optimized. The bionic robotic fish has good sealing properties in water and can adjust its posture to achieve the flipping and pitching functions. In 2019, the School of Mechanical Engineering, Baicheng Normal University (Wang et al. 2019a) proposed the concept of 'fundamental wave', including deformation description and linear density description, established the fish body wave model of the bionic robotic fish, formed the control method system of the multijoint bionic robotic fish's stable swimming propulsion, and achieved the efficient and stable swimming of the bionic robotic fish. In 2022, an underwater soft robot was successfully developed by a joint team from the Max Planck Institute for Intelligent Systems in Germany, Seoul National University in South Korea, and Harvard University in the United States (Ning et al. 2022). The robot can swim underwater like a fish and automatically adjust its swing in the water according to the speed of the water. To design the controller for the robotic fish, the research team developed a data-driven, lumped parameter modeling method, which allows for accurate but lightweight simulations using experimental data and genetic algorithms, and the model can accurately predict the robotic fish's behavior at drive frequency and pressure amplitude, including the effects of antagonistic cocontraction on soft actuators (Li et al. 2023). Currently, most of the simplified mathematical models are used for control. Still, the accuracy of the simplified mathematical models is poor, and the robustness of the control system is poor, which makes the underwater bionic robots designed by this method have poor adaptability to the underwater environment.

2.2 Central pattern generator (CPG)

The main control principle of the CPG is to utilize the mathematical model of the neuron network to drive the joint movement by imitating the movement law and biological control mechanism of the animal itself. The School of Intelligent Systems Science and Engineering at Harbin Engineering University (Wang et al. 2019b) used four oscillators to construct a CPG network model to control the pectoral fin and tail fin with two degrees of freedom of multimode bionic robotic fish, which introduces the angle between the head and tail axis and the horizontal plane and the yaw angle as feedback information to control the swimming posture of the robotic fish and conducted in-depth discussion on the motion control of the pectoral fin. The basic swimming strategy is developed based on Walker's oscillating pectoral fin model. Based on the multijoint robot fish model, the National University of Singapore extracted two basic imitation swimming modes, 'cruise' and 'C-type sharp turn', from the swimming observation of real fish as training samples. The general internal model imitates the CPG of the nervous system used to learn and regenerate the coordinated behavior of fish. This learning method can use general function approximation capability and time/space scalability to generate the same or similar fish swimming patterns by adjusting two parameters. The learned swimming mode was realized in the experiment of multiarticular robotic fish (Ren et al. 2013) (Fig. 4a). Waseda University built and studied a CPG network with nonlinear oscillators for the gait generation of robotic fish and developed a robot that uses a CPG for fish-like motion underwater. These studies reveal that CPG-based approaches are easy to design, fast to implement, and capable of online adjustments (Chen et al. 2020) (Fig. 4b).

The CPG model includes four input parameters, namely, flutter amplitude, flutter angular velocity, flutter offset, and the time ratio of the beat phase to the recovery phase in the flutter. The robot fish developed by the South China University of Technology is equipped with three infrared sensors installed on the left, front, and right sides of the robot fish, as well as an inertial measurement unit that can sense the surrounding obstacles and the direction of movement. Based on these sensor signals, CPG-based closed-loop control can drive the robotic fish to avoid obstacles and track the specified direction (Chen et al. 2021b) (Fig. 4c). The Peking University-developed robotic fish uses CPG modeling as a nonlinear oscillator for joints to realize coordination by altering the connection weights between joints. The online gait generation method based on CPG makes the transition between swimming gaits elegant and smooth to realize multimode swimming and achieve a more realistic movement. By changing the CPG parameters, various swimming patterns can be obtained to simulate the various movements of real fish in nature or designed based on special tasks (Zhao et al. 2006) (Fig. 4d). The Chinese Academy of Sciences (Yu et al. 2016) proposed a particle swarm optimization (PSO)-based CPG control system for underwater vehicles. In general, the parameters of the CPG are determined manually based on experience and computer numerical simulation. In this method, the traveling wave parameters of robotic fish are given manually, and 19 parameters, such as the optimal CPG connection weight, self-inhibition coefficient, and time constant, are selected through the PSO algorithm according to the fish body wave equation. Simulation and experiment show the effectiveness of this method. The Hirose Laboratory of Tokyo Institute of Technology (Nagai and Shintake 2022) adopted the CPG control network comprising this oscillator to control the robot, that is, a multijoint snake robot. The robot has 10 actuating units, constituting a bilateral wave propulsion mechanism with bionic left and right counter muscles. The CPG control network can generate rhythm joint angle control signals and achieve the yaw maneuvering of the robot. The simulation test confirms the feasibility and effectiveness of the control system (Alexander 2017). This control method simulates the central nervous system well, generates continuous and coordinated control signals, and then gives timely feedback to different environments. This method is conducive to coordinated control and has a better environmental adaptation effect, so it is widely used.

Fig. 4 CPG controls the bionic robot. **a** Robotic fish covered with waterproof tape swimming in the water (Ren et al. 2013); **b** Fabrication process of the silicone tail and the outer view of the robotic fish (Chen et al. 2020); **c** Closed-loop CPG-based control can drive the robot fish (Chen et al. 2021b); **d** Prototype of multimode robotic fish (Zhao et al. 2006)

2.3 Sinusoidal controller control method

A sine controller is a kind of control method that is widely used by researchers based on the fact that the waveforms and motion periods generated by how fish are propelled are similar to sine functions. Thus, the sine controller simplifies the motion process of fish into the frequency, amplitude, and waveform of the sine function and then controls the motion of each joint of the underwater bionic robot through these parameters. At the same time, it changes the motion state by relying on the phase difference of the motion between different joints of the robot. The advantages of this control mode are simplicity and easy controllability. In 2015, the robot fish 'Pike' was born at the Massachusetts Institute of Technology; the hardware system of the robot fish 'Pike' includes a head, a pectoral fin, a tail fin, a dorsal fin, a main servo sine controller system, a pectoral fin servo system, and a battery (Li 2015). In 2014, the Tokyo Institute of Technology developed a self-propelled robot dolphin with two joints and an autonomous drive controller (Nakashima and Karako 2014). The robot dolphin is a simplified model of a high-speed swimming marine creature with a length of 1.7 m, which is very close to the size of the actual dolphin. The robot dolphin has a linear body and a rectangular tail fin. An air motor drives the first joint, and the second is driven by a spring. A measurement system is developed to measure the torque and angle of the first joint. The Polytechnic University of Milan (Bottasso et al. 2008) successfully controlled a pair of pectoral fin joints and caudal-fin joints of a robotic fish by using a sinusoidal controller and vibrator (a topology with three oscillators adjacent to each other). By movement of pectoral and caudal joints, the robot can achieve various underwater swimming actions. The experimental results show that the control method can realize stable swimming. Due to the uniqueness of the function types in the controller, this method has limitations. If there is a motion mode that does not belong to the function characteristics, it cannot be accurately regulated. In addition, this control mode has poor adaptability when dealing with the sudden change of control parameters, and it cannot quickly adjust from one motion mode to another, leading to poor environmental adaptability of the robot.

2.4 Rigid motor drive

Most marine bionic robots are driven by rigid motors. Since motor-driven robots are easier to implement in terms of systems than flexible-driven robots, which can fully use the high energy density and high efficiency of motors, rigid motor-driven bionic robots are more convenient for specific purposes (Karthik 2014). They are currently more mature in development than flexible-driven bionic robots. For rigid motors, waterproof housing is often needed, with high sealing requirements and greater challenges in terms of water pressure (Dawson and Allison 2020).

For bionic robots driven by rigid motors, there are mainly single-motor drives and multimotor drives. Multimotor drive means that the system has more flexibility, but there are more limitations regarding structure and size, and it can carry many functional sensors. Examples include the UK Natural Environment Council's (NERC) 5.5-m long 1800 kg-dry weight Autosub6000 AUV, which is rated to a depth of 6000 m, can be equipped with a variety of payloads for marine geoscience research, includes high-resolution multibeam echo sounders, seabed profilers, and side-scan sonar, color camera systems, conductivity, temperature, depth, and electrochemical redox (Eh) sensors. It has precise navigation and terrain tracking capabilities and has a sophisticated collision avoidance system (Wynn et al. 2014) (Fig. 5a).

The Robotics Institute of Beihang University successfully developed the bionic robotic eel, bionic robotic dolphin, experimental small robotic fish, and trail-tail bionic robotic fish SPC-I, SPC-II, and SPC-III (Wang et al. 2005) (Fig. 5b) driven by an electric motor and wireless remote-control rigid actuator (Li and Jiang 2012), as shown in Figs. 5c and d. Compared with conventional motor-driven robots, the maneuverability of the bionic underwater robot is significantly enhanced. This series of robots were applied to underwater archaeological discovery, experimental teaching, ocean cruise experiments, and water quality detection and achieved good results. The Harbin Engineering University-developed bionic underwater robot is driven by two servo rigid motors with tail fins and an interactive gear system, which can achieve various complex movements, as well as two articulated serpentines, HRF-I and HRF-II bionic robotic fish (Tian et al. 2022a). Compared with the former, the latter can achieve steering, snorkeling, and reversing, and the performance in all aspects has been greatly improved. The Department of Computer Science at the University of Essex conducted experiments with a rigidly driven robotic fish G9 equipped with a variety of sensors and found that it can respond to dynamic changes in its environment, capturing its position in the tank and the robot's posture and internal state, with good drive performance (Liu and Hu 2006) (Fig. 5e). The New York University Institute of Technology designed a robot's body shell comprising a payload and a motor bay. The payload bay contains control electronics, batteries, and counterweights to enhance pitch and roll stability and achieve appropriate buoyancy. More specifically, buoyancy is set so the robot is almost completely submerged during operation. The cap provides a waterproof seal for the payload bay and extends toward the rear of the robot, partially covering the engine room. A toggle switch hidden in the lid extension turns the robot on or off. The motor compartment houses a Traxxas 2065 waterproof servo motor for the drive, which is connected to the rear by an

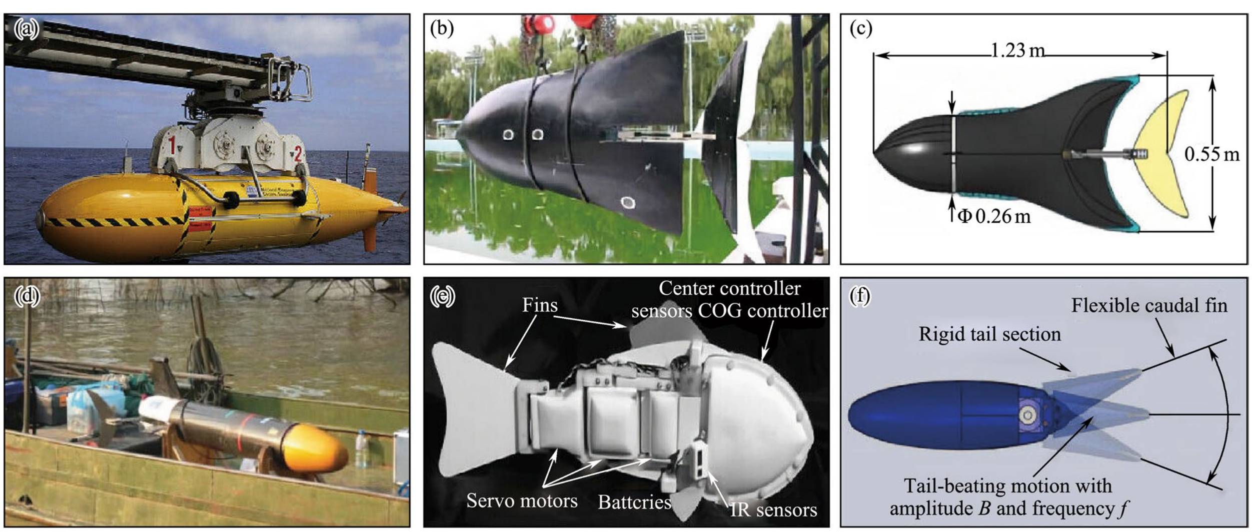

Fig. 5 Rigid motor-driven robot. **a** AUV submarine (Wynn et al. 2014); **b** SPC-I (Wang et al. 2005); **c** SPC-II (Liang et al. 2011); **d** Working environment of SPC-III in the Taihu Lake (Liang et al. 2011); **e** G9 robotic fish profile (Liu and Hu 2006); **f** Top view of the robotic fish representing the robot's undulating tail (Kopman and Porfiri 2013)

improved servo motor horn. The caudal fin is snug in a slit at the free end of the caudal fin (Kopman and Porfiri 2013) (Fig. 5f).

Single motor-driven marine bionic robots are often used in fish bionic robots, which have a single function and are not flexible enough in movement, such as the bionic fish studied by Northern Research Center for Science and Technology at Malek Ashtar University of Technology (Sabet and Nourmohammadi 2022) and the voice-activated soft robot fish studied by Robert. The Massachusetts Institute of Technology (MIT) Distributed Robotics Laboratory developed a single-motor driven robotic fish, a soft robotic fish system whose subcomponents include an elastomeric tail, an external gear pump, two diving surfaces, and control electronics, including an acoustic receiver and a fish eye-eye camera that can complete underwater reconnaissance missions (Katzschmann et al. 2018) (Fig. 6a). The robotic fish designed by the College of Worcester employs a flexible body with embedded rigid actuators that mimic the elongated anatomical form of a fish. Also, the robot has a novel fluid drive system that drives body movement and has all the subsystems of traditional robots: power, drive, handling, and control. A set of fluid elastomer actuators is at the heart of the fish's soft body. The soft robot has an input-output relationship similar to a biological fish, allowing it to be self-sufficient and capable of fast movement (Marchese et al. 2014) (Fig. 6b). The Electrical Engineering and Computer Science Department of the University of Michigan (Ozog et al. 2017). The robot adjusts its height through a buoyancy module, and a motor in the tail provides power and adjusts its direction. The flexible part of the robotic fish, designed by the State Key Laboratory of Complex Systems Management and Control at the Institute of Automation, Chinese Academy of Sciences, consists of three joints connected by an aluminum exoskeleton. Each joint is connected to an R/C servo motor that controls the rotation angle of the joint. The rubber caudal fin is connected to the third segment by the peduncle and is crescent-shaped with good coordination (Yu et al. 2016) (Fig. 6c). The robot fish designed by the University of the Chinese Academy of Sciences employs a magnetic actuator as a motor. The propulsion system is characterized by remote control using Bluetooth low power and easy operation through smart devices. By the electromagnetic induction law, the robot fish can swim quickly and turn flexibly. This miniature robot fish could be employed for animal behavior research and special underwater tasks (Chen et al. 2017) (Fig. 6d).

The Key Laboratory of Marine Engineering in Shandong Province developed a motor-driven robotic fish with artificial side-line sensors that can help enhance the fish's maneuverability in dark environments. Artificial sidelines simulate the structure of fish sidelines, offering possibilities for underwater sensing technology and robotic fish control (Salumäe and Kruusmaa 2013) (Fig. 6e). Researchers from Shahrud University of Technology studied a robotic fish with a streamlined drive body and a flexible tail, comprising a network of pressurized liquid-filled chambers embedded in an elastic beam.

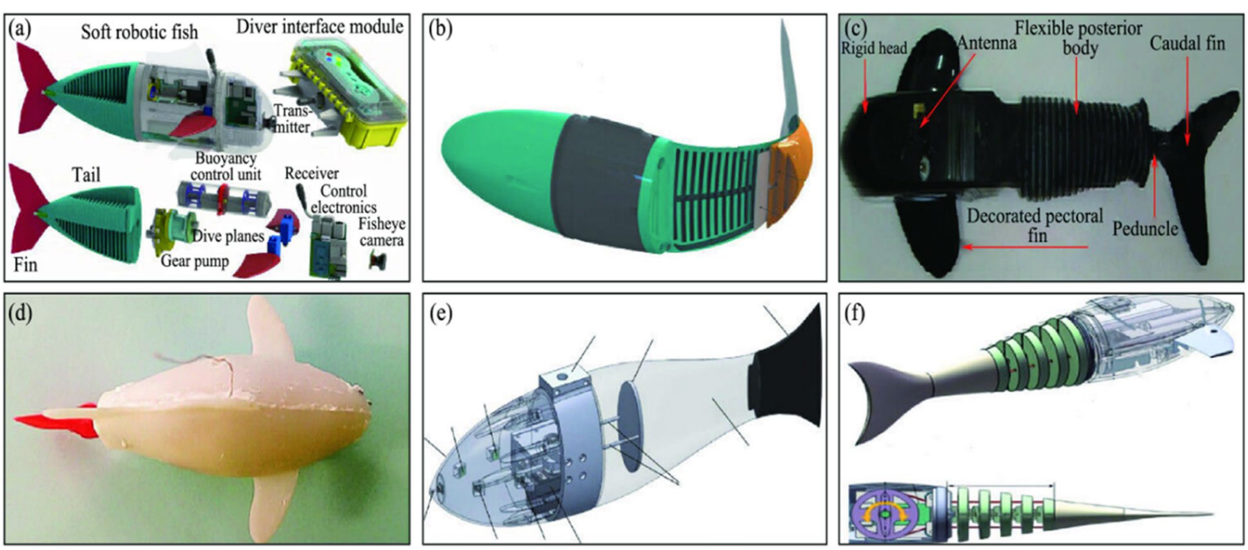

Fig. 6 Single motor-driven bionic robot. **a** Soft robotic fish and diver interface module (Katzschmann et al. 2018); **b** Details of a soft-bodied robotic fish (Marchese et al. 2014); **c** Prototype of the robotic fish applied to the underwater robot competition (Yu et al. 2016); **d** Mechanical design of the robotic fish (Chen et al. 2017); **e** FILOSE robot fish (Salumäe and Kruusmaa 2013); **f** Robot fish with a wire-driven active body and compliant tail (Haji and Bamdad 2022)

Viscous fluids with different pressures flow in the channel, producing normal and shear stresses in the channel, which can make the robot fish adapt to different water pressure environments (Haji and Bamdad 2022) (Fig. 6f).

The salamander robot has a modular design comprising seven drive elements and a head element (with the same appearance as the others). The housing of each element includes two symmetrical parts molded with a lightweight polyurethane resin. These components are connected using compatible connectors fixed to the output shaft. All output axes are aligned, so plane motion is produced. To ensure that the robot is waterproof, a custom O-ring robot is used with a total length of 77 cm. Asymmetric friction with the ground, which is required to crawl on the ground correctly, is achieved by fixing a pair of passive wheels to each element, thus ensuring a coordinated transition between swimming and crawling of the robot (Crespi and Ijspeert 2008) (Fig. 7a). The four-legged starfish-shaped soft swimming robot's flexible and natural buoyancy offers many advantages for tasks such as underwater exploration, sample collection, and marine wildlife observations (Du et al. 2021) (Fig. 7b). In Fig. 7c, the swinging body of the bionic robotic fish is a multilink mechanism connected by hinges and equipped with multiple motors. In swimming, the required body curve can be acquired by adjusting the relative position of each connecting rod, optimizing its control performance and swimming efficiency compared with a single motor (Korkmaz et al. 2012). Inspired by the amphibious tortoise, the mother robot is designed with a spherical body, four legs, and two degrees of freedom. Powered by 4 vector water jets and 10 servo motors, it can walk on land and cruise underwater (Shi et al. 2013) (Fig. 7d). The enhanced 3D printing, low cost, multifunction, high mobility, tortoise-like environmental monitoring, and data acquisition mobile amphibious spherical robot by Beijing Institute of Technology has good amphibious performance (Guo et al. 2018) (Fig. 7e). The cuttlefish robot studied by the University of Nevada researchers is powered by two soft fins of multiple embedded IPMC drive motors connected to an Eco-Flex membrane. The traveling wave is generated on the soft fin by drive, the deformation and blocking force of IPMC on the soft fin are measured, and the actuator is characterized, which can have good wave swimming performance in water (Shen et al. 2020) (Fig. 7f).

Recently, bionic amphibious robots have developed profoundly in bionic structure design, movement performance, and outdoor workability. Researchers from Harbin Engineering University (Li et al. 2021) developed a shape-shifted bionic turtle that can travel in water and walk on land. To enhance the reliability of bionic robots in the future, these robots designed for engineering applications are driven by electric motors and are constantly improved. However, due to their performance limitations, large size, and high power consumption, the size and range of motors have become significant limitations.

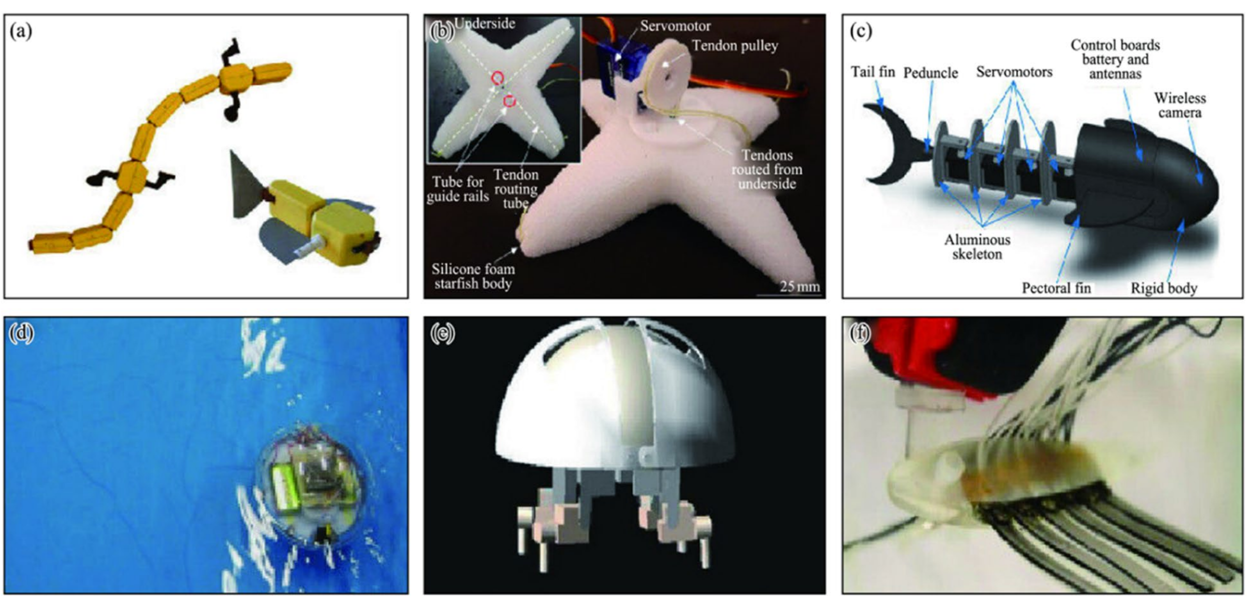

Fig. 7 Multimotor driven bionic robot. **a** Salamander (left) and fish (right) robots (Crespi and Ijspeert 2008); **b** Soft starfish (Du et al. 2021); **c** Demonstration of the body curve fitting method (Korkmaz et al. 2012); **d** Prototype of the spherical mother robot (Shi et al. 2013); **e** Amphibious spherical robot (Guo et al. 2018); **f** Multimotor driven fish robot (Shen et al. 2020)

2.5 Soft actuator drive

For bionic robots driven by responsive soft actuators, often by imitating the movement patterns of marine organisms, artificial muscles are used to cause propulsion by deformation under control of voltage, and although their power and precision cannot be compared with those of electric motors, responsive soft actuators are stimulated to perform better in terms of high adaptability due to their excellent compliance.

Meanwhile, soft actuator-driven bionic robots are widely used in some miniature marine robots because of their smaller size requirements due to the absence of motors, and soft actuators also have a huge advantage regarding range because they usually consume less power when used compared to motor drives (Gao et al. 2022). In 2018, the Precision Engineering Institute designed a new robotic fish with an active and compliant propulsion mechanism, a maximum swimming speed of 2.15 body lengths per second, and a maximum instantaneous turning speed of 269°/s (Shintake et al. 2018). In 2014, Marche University of Technology designed a Carregi-shaped swimming robot through a multiphysics simulation environment, which can change from a bone-like motion to a Caran-shaped motion (Praczyk 2014).

The Harvard University-designed completely soft octopus robot has all parts of its body made by 3D printing technology and feels slightly slimy to the touch. The soft robot has morphing and cushioning and can travel through small, irregular spaces, which can be useful in the medical, military, and exploration fields (Wehner et al. 2016) (Fig. 8a). The octopus robot, developed by Queen Mary University of London, is made entirely of soft materials and employs a new fluid drive mechanism that allows the robot to push forward, change direction, and rotate around its main axis. In addition, it can use multiple tentacles to grab objects or propel them underwater (Fras et al. 2018) (Fig. 8b).

The soft-bodied fish developed by Zhejiang University is powered entirely by a soft electroactive structure made of a DE and an ionic conducting hydrogel. The robot fish can swim at a speed of 6.4 cm/s (0.69 body length per second), which is much faster than a soft responsive material-powered previously reported soft robotic fish (Li et al. 2017) (Fig. 8c). In Fig. 8d, the flexible robotic fish is a transitional stage between rigid robotic fish and

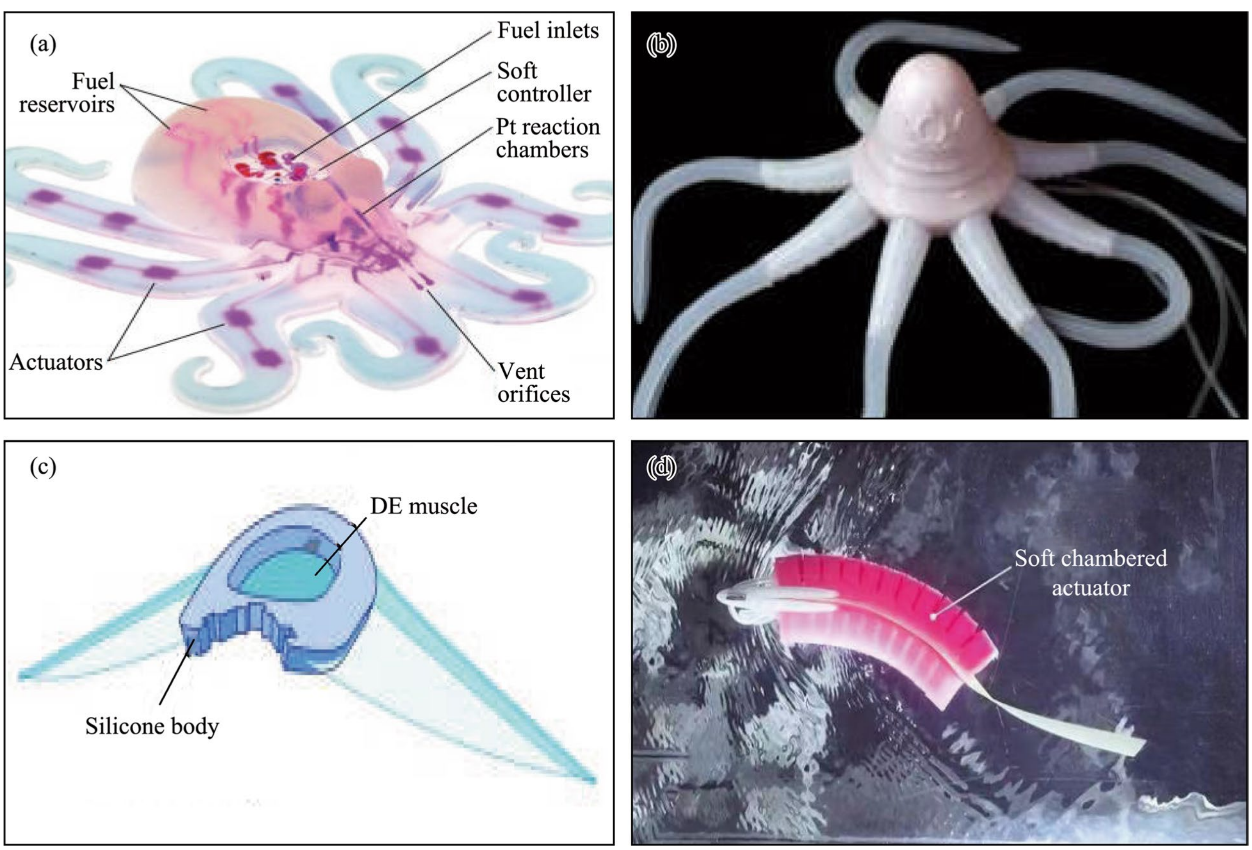

Fig. 8 Soft actuator-driven bionic robot. **a** Octopus robot (Wehner et al. 2016); **b** Multitentacle fish robot (Fras et al. 2018); **c** Soft electronic fish (Li et al. 2017); **d** Whole body stiffness research (Chen and Jiang 2019)

flexible robotic fish, with typical soft materials and traditional driving methods (Chen and Jiang 2019). Because the soft material has large elastic deformation, it can be restored to its original shape, and the soft material of the robot fish can be used to protect the actuator and waterproof (Liu and Jiang 2022). With the development of bionics and materials science, marine release robots are increasingly driven by a variety of methods, and typical stimulus-responsive actuators include IPMC, SMA, responsive hydrogels, pneumatic structures, chemically responsive expanded fluid networks, and living cells (Bai et al. 2021). Using simple principles and widely available materials, the highly integrated electric drive module not only eliminates bulky pumps, pipes, and other equipment but also enables precise control of deformation, while the compact form factor also increases portability.

3 Bionic robot drive mode and control strategy

Traditionally, underwater robots have been classified based on Breder's fish classification: if a fish generates thrust by bending its body/or caudal fins, the resulting motion is classified as a BCF motion. Fish such as eel-shaped, flesh-capsule, tuna, eel and shark can be categorized into BCF types (Jiao et al. 2022). However, suppose that fish uses their mid-fin (including anal, dorsal, and pectoral fins) or paired fins (including ventral and pectoral fins) as propulsion mechanisms, the resulting swimming pattern is classified as a mid-fin or paired fin (MPF) movement (Wang and Wang 2014). Regardless of the mode of propulsion used, fish movements are characterized by deformed bodies, fluid forces, and their interactions. Moreover, each mode of motion can be classified by wave frequency as fluctuating and oscillating, as can be seen in fish movements.

Oscillatory motion can be applied when the fish generates propulsion from wave-like motion. Otherwise, if the fish uses a rotation-like motion to obtain thrust, this motion can be classified as oscillatory. These two classifications cannot be separated because oscillatory motion can be derived from the fluctuating motion of shorter wavelengths and vice versa. Eels, which usually use their whole body to produce wave-like motions, can be classified as fluctuating motions, while box fish, which only make their tail fins swing due to body inflexibility, can be classified as oscillatory motions. However, in this fish-based classification, problems emerge in the general classification of animal species (Zhang et al. 2017). Especially in robotics, there is no restriction to imitate the motion mechanism and shape of fish. Following the traditional fish classification is still difficult if the motion mechanism and shape of the robot are somewhat different from the target animal.

Thus, in this review, a simplified classification model for the robotics domain is put forward. First, similar to BCF- and MPF-type motions in the fish classification, robots can be classified as body or tail-end anal (BCA) and mid-end or paired anal (MPA) (Wang et al. 2022). BCA and MPA are classified based on where the drive occurs relative to the central axis and the direction of robot propulsion. BCA achieves propulsion through drive motion along the central axis. However, in MPA, the driving motion occurs outside the central axis. Similar to the fluctuating oscillation classification of fish, the subcategory is set to fluctuating oscillation motion based on the motion of the robot actuator. Like in the fish classification, the fluctuating motion can be expressed as the fluctuating motion in the actuator. In the same way, oscillatory motion refers to the propulsion structure that rotates on its fixture instead of the wave-like shape.

3.1 Robot drive mode classification

3.1.1 MPF model

The movement modes of fish are classified by body parts used by fish for propulsion into BCF propulsion mode and MPF propulsion mode (Zhou et al. 2023). In MPF propulsion mode, the dorsal, ventral, pectoral, and anal fins are mainly utilized as the main propulsion parts, which can maintain high mobility, stability, and swimming efficiency at low speed. In general, it can achieve accurate six degrees of freedom movement, underwater position holding, and steering, but it is difficult to achieve high-speed swimming and acceleration performance is insufficient. Lampreys, an eel MPF swimming robot developed by the Marine Science Center of Northeastern University, uses 10 TiNi filaments of 250 μm to be energized and heated as a motor (Wu et al. 2013). It has a simple structure, no noise, and good stealth performance. The fishtail propulsion of the robot designed in this mode is quieter than the traditional propeller, which is especially important in future naval battles. It can greatly improve stealth ability. Japan developed the first MPF robotic fish that can swim freely underwater; this bionic robotic fish is 650 mm long, 500 mm wide, and 0.64 kg, with floating, diving, turn signal, and other functions, and the smooth shape of the robot fish makes the efficiency of the fishtail propeller up to 80% (Scaradozzi et al. 2017). It uses the three-joint bionic tail fin as the only power source, with low power consumption, which can extend the battery life and is suitable for long-term underwater cruises, tracking, and other tasks. In 2021, Osaka University developed a pair of miniature fish out of silicone, which was only the size of a hand but could swim at 0.1 m/s (Xie et al. 2021). In 2017, Festo, a German company, developed the pectoral fin bionic robotic fish aqua ray with a body length of 615 mm, a wingspan of 960 mm, and a maximum speed of 0.5 m/s (Saxena and Chauhan 2017). The mechanical operation process of forward, backward, differential turning, pitching, and other actions of the bionic robot was completed by experiments and tests, completing the goal of the project. In 2009, the China Academy of Automation developed a small robot dolphin that is 560 mm long and weighs about 3.3 kg, which can complete special tasks such as marching, chasing, and searching (Xia et al. 2023). The National University of Defense Technology in China produced a prototype of a bionic pectoral fin powered by multiple fins. In the water tank experiment, the robot's left and right fins moved simultaneously, with a forward speed of 0.13 m/s and a backward speed of 0.15 m/s. Due to the symmetrical structure and movement of the wave fins of the robot, they could smoothly change the gait from forward to backward without turning and move laterally by sending inward counterpropagation waves.

The Institute of Robotics of Beihang University and the Chinese Academy of Sciences successfully developed SPC-II bionic robotic fish, the first practical application of MPF bionic robotic fish in China (Lou et al. 2017). The SPC-II bionic robotic fish is 1.23 m long, with a shiny black body, a total weight of 40 kg, and a maximum diving depth of 5 m. It has a prominent camera above its head that collects location data. The SPC-II bionic robotic fish can move, sink, and float freely and flexibly in waves. The MPF bionic robotic fish robot-ray I, robot-ray II, robot-ray III, and robot-ray IV series were developed by Beihang University (Wu et al. 2021a). Among them, the best-performing robot-ray IV is 320 mm long with a wingspan of 560 mm. The maximum swimming speed is about 0.16 m/s. Moreover, the robot fish has high underwater speed and better load capacity, and the underwater movement trace is smaller. It can perform quick close-in intercepts, search for enemy divers, highly maneuverable patrols, and track underwater targets at high speeds. The bionic underwater vehicle based on the MPF long-wave propulsion principle has the advantages of high mobility, strong anti-interference ability, and environmental friendliness (Korkmaz et al. 2015). Thus, research on this bionic underwater vehicle has a broad market prospect and application value.

3.1.2 BCF model

BCF propulsion mode enables most fish to swim by waving or swinging part of the body and tail fin using eddy currents to push the water behind to use the water reaction force to achieve the forward movement of the fish body. When cruising at high speed, high swimming efficiency can be achieved, generally, more than 80%, and the acceleration and starting performance are good. The bionic bull nose shark designed by Beihang University is a BCF robotic fish (Wang et al. 2021). The width of the first-generation bull nose shark robots is 28–46 cm, while that of the second-generation one can reach more than 110 cm. The robot fish is driven by two motors on both sides of the pectoral fin (60W DC motor drive); the flexible pectoral fin comprises silicone rubber material, the main material is made up of relatively low-density glass fiber, and the addition of gyroscopes can achieve autonomous navigation function. A steering engine drives the BCF robot eel developed by the Beijing University of Technology. The fin material is a composite material that can be applied to the eddy current environment with a large water flow (Song et al. 2013). The robot shark, developed by St. Mary's College, University of London, also adopts the BCF drive mode (Watts and McGookin 2014). It is larger and adopts silicone fins, and the head's central processor controls the robot's movement, which can swim upstream in the rapids. The robot shark simulates a shark's shape and swimming mode, with little disturbance to the environment and no harm to underwater organisms. The multilink glider robot, developed by the China Academy of Electronics and Information Technology, can swim flexibly and glide efficiently in 3D space and is equipped with the main BCF of a three-degree-of-freedom buoyancy drive system as the main propulsion device for stable propulsion in water (Wang et al. 2021) (Fig. 9a). A Lanzhou Jiaotong University-designed BCF-propelled four-fin bionic prototype based on modular design has high efficiency, rich turning modes, good maneuverability, and high turning speed (Li et al. 2018) (Fig. 9b). Jilin University has developed a carpal bone robot fish with a four-degree-of-freedom tail. The robot fish has two modes of radio control and autonomous swimming. The BCF mode has outstanding performance of high speed and high efficiency (Yan et al. 2008) (Fig. 9c). Ferat University in Turkey has developed a bionic boat-shaped autonomous robotic fish prototype with a double-link tail propulsion mechanism. To simulate the robust swimming gait of fish, a bionic motion control structure based on CPG is adopted. The unidirectional chain CPG network designed is inspired by the neural spinal cord of lampreys and is propelled by BCF. It produces a steady, rhythmic pattern of oscillations underwater (Ay et al. 2018) (Fig. 9d).

In 2015, the Harbin Institute of Technology successfully developed a double-jointed Karan-shaped fish robot, code-named 'HRF-I', with a swimming speed of 0.5 m/s (Wang et al. 2015). In 2018, the University of Science and Technology of China designed a four-joint bionic robotic fish based on the morphological structure and movement form of the Karan-shaped fish (Zhong et al. 2018). In 2016, a BCF model bionic eel robotic fish with eight joints was developed in the United States, and

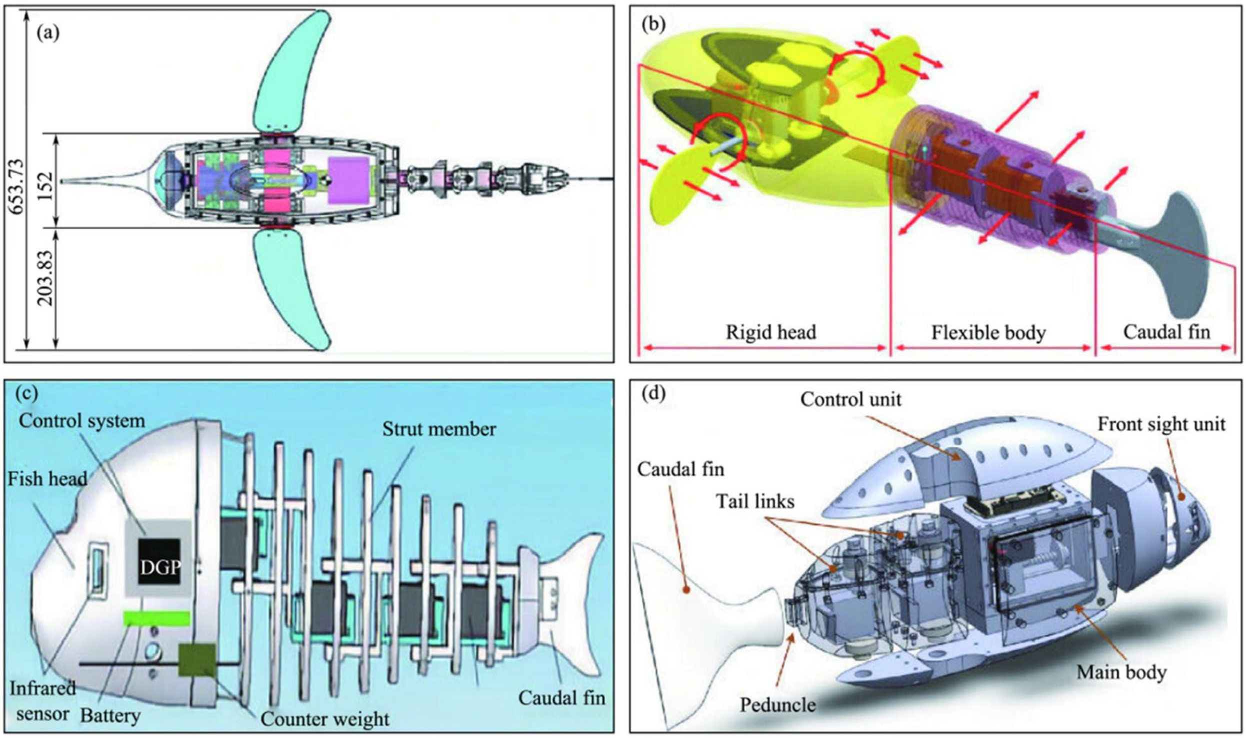

Fig. 9 BCF mode swimming robot fish. **a** Main components of the FishBot (Wang et al. 2021); **b** Prototype of the proposed robotic fish (Li et al. 2018); **c** Mechanical structure of the robotic fish (Yan et al. 2008); **d** Detailed mechanical configuration of the robotic fish (Ay et al. 2018)

in 2017, Beihang University developed a series of fibular bionic robotic fish with two parallel joints in the tail stalk and tail fin, driven by a two-axis servo motor (Yu et al. 2017). The simulated or caudal-fin BCF pulsating underwater thruster, developed by Osaka University in Japan in 2017, has flexible fins on both sides and is driven by 16 DC servo motors via the top fins. The robot fish can realize flexible underwater movements such as surface, diving, steering, pitching, and hovering, which confirms the viability of the application of undulation fin bionic underwater propellers to future underwater robots (Ravalli et al. 2017). Several flexible fish species, such as dolphins, sharks, and tuna, swim in BCF mode and can swim with high speed and efficiency. Based on this design, the BCF mode robot produces thrust by bending the torso and swinging the tail fin, leading to high swimming speed, high efficiency, and fast starting performance; thus, the BCF mode is suitable for applications such as long distance and high-speed swimming, instantaneous acceleration, or fast steering (Rajamohamed and Raviraj 2015).

3.2 Bionic flutter rigid drive

The fluttering rigid drive mode is a structure of self-excited vibration consisting of skeletal, muscular, and nerve centers (Wang et al. 2021). It is the main mode of large aquatic animals with large spreading chord ratios and thickness, such as turtles and penguins. It uses periodic changes in the bending and sinking posture of the up and down swinging forelimbs to regulate the water's angle of approach. It can be controlled independently of the winging posture to produce forward thrust of the swim front itself, where the forelimbs swing in a process that produces orthogonal directional (negative) drag and lift forces, prompting the body to keep advancing (Todd et al. 2020). Although large, this biological body has the advantages of explosive power, high efficiency, stability, low noise, excellent maneuverability, and operational performance. Several theoretical and experimental works have been conducted on marine fluttering organisms by combining bionics from several disciplines. Based on this, a series of bionic flutter wing propulsion devices have been developed with beneficial results. The Chinese Academy of Sciences designed a four-joint robotic fish head, which is a hollow, rigid, and streamlined shell made of molded glass fiber that provides enough space for electromechanical components such as control circuits, sensors, rechargeable batteries, and balancing heavy objects. To duplicate the movement of fish, a series of multilink rigid motors connected by yaw joints are used as the main propulsion mechanism, followed by a slender tail shaft made of polyvinyl chloride and then a polyurethane tail fin with some elasticity. All the rods, driven by DC servo motors, are connected in series to a metal skeleton covered with a flexible waterproof skin that allows for flexible turns in water up to 213° (Su et al. 2014) (Fig. 10a). The robot adopts motor modularity to facilitate loading and unloading. In Fig. 10b, the Nanyang knife-fish robot contains three independent modules, namely, the buoyancy box module, power cabin module, and wave fin module. Because these modules are designed in a modular manner, these modules can be easily replaced if the design changes or additional features need to be attached (Low 2009).

To investigate the effects of electric motors on robotic fish, the University of Essex in the United Kingdom performed production tests on the G9 series of robotic fish, which are about 52 cm long and have three or four servo motors and two DC motors (Liu and Hu 2010) (Fig. 10c). The servo motor is connected at the tail as three joints; the head is fitted with a DC motor that changes the fish's center of gravity, and another controls a miniature pump that adjusts the robot's weight by pumping water. Enhancements in the mechanical structure and skin materials have improved the efficiency and robustness of the robotic fish. The robot fish, NAF-I, weighs about 6.8 kg and is 650 mm long, 100 mm wide, and 260 mm high. It is powered by a 15 V nickel-metal hydride battery, allowing the fish prototype to swim for up to 4 h when fully charged. One DC motor drives the oscillating tail fin, and the other drives the counterweight, and the robot swims in a straight line at a speed of about 0.35 m/s, equivalent to about half a body length per second. It is also confirmed that the greater the thrust of the motor on the robot fish, the faster its swimming speed (Chong et al. 2009) (Fig. 10d). To produce greater thrust, the choice of motor parameters becomes very significant.

Research on bionic flutter drive systems has never stopped. Still, due to the complexity of the drive mechanism and its unique motion characteristics and the different research methods, the forms of flutter wing propulsion are also different (Zhu 2018). So far, it has been impossible to conduct a theoretical study for various bionic drive mechanisms because many crucial technical and theoretical problems remain in the research stage, and the technical design of various bionic propulsion systems is still very backward and far from practical application.

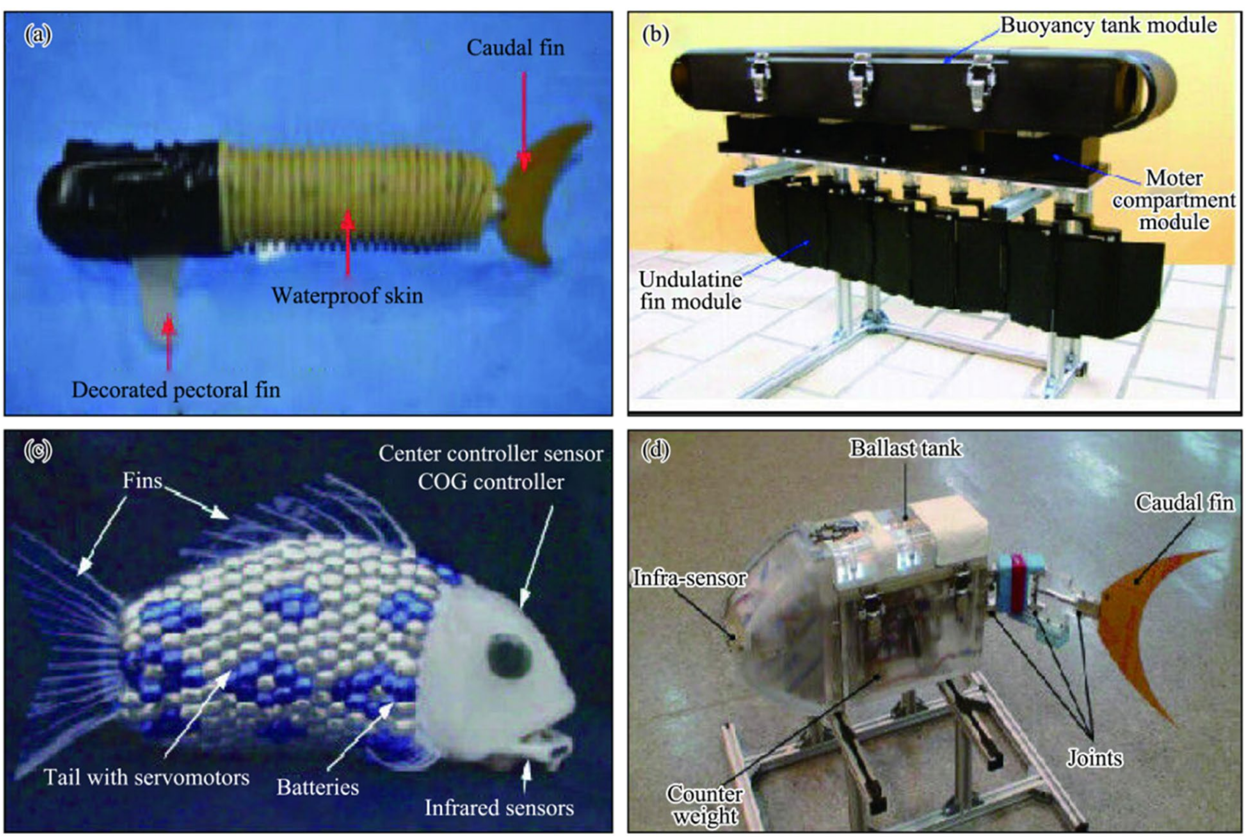

Fig. 10 Flutter rigid drive robot. **a** Slim fish robotic prototypes applied to C-start experiments (Su et al. 2014); **b** Southern Ocean knife-fish module (Low 2009); **c** Schematic structure of a G9 series robotic fish (Liu and Hu 2010); **d** Prototype of biomimetic fish, NAF-I (Chong et al. 2009)

3.3 Bionic wave oscillation rigid drive

At present, the main biomimetic fish propulsion systems are BCF models, such as dolphins, which are propelled by the caudal fin, and MPF models, such as manta rays, which are propelled by the pectoral fin.

The propulsion model has high thrust, stability, and maneuverability (Jung et al. 2002). It has an excellent performance in fast swimming under hydrostatic conditions and better start and stop functions but poor maneuverability in low-speed turns and turbulent environments. Peking University developed a robot fish consisting of a rigid head, a flexible body, and a tail fin. The hard head houses a control unit, a wireless communication module, and a set of batteries. The battery is placed at the bottom of the head to ensure the vertical stability of the robot while swimming. A pair of pectoral fins are fixed on both sides of the head to ensure the stability of the fins in water. The flexible body comprises three joints, each connected to a servo motor to adjust the deflection angle of the joint. The rubber tail fin is fixed on the third joint and acts with the water flow to move forward in waves (Li et al. 2014a) (Fig. 11a). Developed by the Institute of International Education, the HRF is a new type of marine robot with different modes of motion to adapt to the complex marine environment. The motion mode of the hybrid robot fish mainly has two types, namely, sail drive and wave drive. The HRF includes tail fins, wings, steering rubber, collapsible sails, and a hull. In wind-driven mode, the sail is folded, while wave drive is used to drive the hydrofoil up and down with waves to provide power; thus, no extra energy is needed to move forward (Ma et al. 2020) (Fig. 11b).

In 2002, MIT developed the world's first robotic fish—bionic tuna—which can complete complex movements such as propulsion, turning, and ascent diving (Koch 2002). Its forward speed can reach 2 m/s, and the propulsion efficiency is as high as 91%. Building on this, the MIT team developed the reinforced fish Robopike and the steel-like underwater vehicle VCUUV in collaboration with Draper Lab in the United States. In 2016, the birth of these two robotic fish greatly improved the BCF mode propulsion technology (Kumar et al. 2016). A hydraulic bionic wave fin prototype is designed at the National University of Defense Technology, comprising a hydraulic pressure source, a hydraulic bionic wave fin principle prototype, and a data acquisition and processing system.

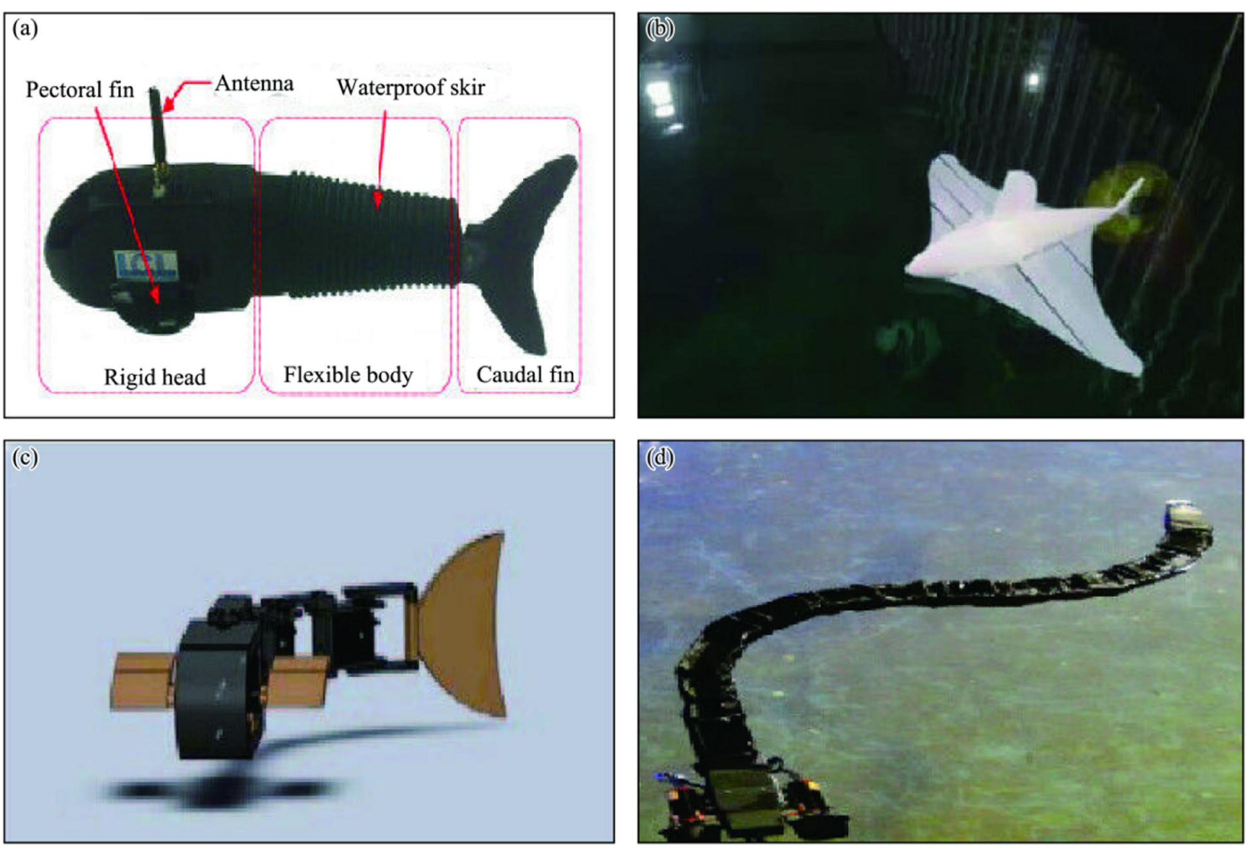

Fig. 11 Wave rigid drive robot. **a** Prototype of the robotic fish (Li et al. 2014a); **b** Prototype of the HRF in wind-driven mode (Ma et al. 2020); **c** BCF mode swimming style (Chowdhury et al. 2011); **d** Amphibious snake robot (Kelasidi et al. 2016)

The flow variation rule, the function principle of bionic oscillating joint movement, the underwater speed test, and the free navigation propulsion test were performed on the prototype. The National University of Singapore developed a fish-like underwater vehicle integrating fish-like swimming, modular link, and fin movement. The motor is used for simulation of the wave of the fish tail, that is, sinusoidal oscillation. The aim is to duplicate the BCF model's propulsion technology to swim efficiently over long distances at impressive speeds (Chowdhury et al. 2011) (Fig. 11c). Developed by the Norwegian University of Science and Technology, the amphibious snake robot has similar kinematics whether on land or in water; the snake robot constantly changes its body shape to reduce ground friction or hydrodynamic resistance to achieve forward propulsion, that is, when the snake robot follows a wavy gait pattern, it gains propulsion (Kelasidi et al. 2016) (Fig. 11d).

3.4 Special drive mode

Various underwater organisms drive in different ways, and simulation methods have always been employed to explore their motion mechanism and optimize their motion to guide the design and production of underwater robots. Several strange underwater organisms also bring inspiration to researchers. For example, there is increasing research on underwater jellyfish octopus. The organism is flexible, and only by changing the size of the cavity does it achieve steering and fixed trajectory movement. However, its swimming stability is poor, and the direction is not easy to control, which is a huge issue to solve. Bionic water snake robots, like water snakes, can swim freely in water by swinging their tails. Their movement is flexible and can complete relatively complex task environments. They have good flexibility and freedom in some locations that divers or other underwater vehicles cannot reach because of their appearance. Turtles in water do not have the same slow movement as on the ground: they swim very fast and are very sensitive. Their unique way of propulsion also offers a lot of inspiration to researchers, especially those who study amphibious robot turtles.

3.4.1 Amphibian drive mode

Since the world's first bionic amphibious robot was designed in 2013, it has gradually developed astonishing achievements. The working environment of the bionic amphibious robot consists of a beach, wetland, underwater, and other complex terrains, and the biological prototype mainly comprises aquatic and terrestrial organisms. Researchers have established many theoretical models such as 'resistance theory', 'slender body theory', and 'inverted pendulum model', but most of them are only applicable to static laboratory environments, and the working environment of bionic amphibious robots is complex and changeable. Thus, it needs to sense the external environment information, parameter change trend, and functional state in real time. In 2010, the Tokyo Institute of Technology Robotics Laboratory designed the serpentine amphibious robot ACM-R5 based on the previously developed HELIX, which had poor performance (Yang and Ma 2010). The robot has a 3D motion capability, and each module has a motion mode of two degrees of freedom, capable of pitching and yawing. It has many gaits on land, but its gait in water has not been studied yet. To make serpentine amphibious robots have more flexible mobility in water, the State Key Laboratory of Robotics of the Chinese Academy of Sciences developed a new amphibious robot called EXPLORER-III in 2020, which consists of nine waterproof modular universal units, each with two free-motion modes of pitch and yaw (Zheng et al. 2020). The robot has a total length of 117 cm, a trunk diameter of 7.5 cm, and a total mass of 6.75 kg. Since 2016, the State Key Laboratory of Robotics of the Shenyang Institute of Automation, Chinese Academy of Sciences, has conducted extensive research on another serpentine amphibious robot and developed a prototype (Yang et al. 2016). The robot is 700 mm long, 320 mm wide, and 150 mm high, with a total mass of 4.995 kg. Moreover, the robot can move at a speed of up to 0.45 m/s in water. Bionic amphibious robots will simplify amphibious drive structures by using soft actuators, improving energy efficiency, sensing the environment, and having a certain ability to make autonomous decisions.

Wheel-propeller-integrated amphibious robots tend to integrate multiple drive units, which can crawl in water and on the ground. Thus, the driving device does not need to be changed; only the mode of motion needs to be changed, which can result in good motion performance on land and in water (Liu and Jiang 2022). Thus, research on such robots worldwide has gradually increased, and researchers have achieved some great results. The Mechanical Engineering and Automation major of Beihang University designed an integrated wheel-propeller amphibious robot, which has a simple and compact structure and can realize autonomous movement in two environments (Wu et al. 2021b). Shenyang Institute of Automation, Chinese Academy of Sciences developed an integrated wheel-propeller amphibious robot with dimensions (L×W×H) of 1.0 m×0.96 m×0.2 m. The total weight is 44 kg, the maximum crawling speed is 1 m/s, the maximum swimming speed is 0.7 cm/s, and the maximum working depth is 10 m (You et al. 2010). Individual motors drive all drives of the robot, and depending on the operating environment, the movement can be easily switched by rotating the wheel-propeller 90°, but it needs to consume a lot of energy, and the energy of bionic amphibious robots is extremely limited, and the efficiency of energy utilization is low, limiting its application. From the perspective of broadening income sources and reducing expenses, on the one hand, bionic amphibious robots must carry batteries with higher energy density and enhance outdoor energy collection capabilities.

Revealing the movement characteristics of biological prototypes is the premise of bionic design. Due to the rapid development of biology, chemistry, structural science, and other disciplines, research on the driving mechanism of various underwater and land animals has gradually entered the muscle tissue structure and microcell energy utilization process. More accurate mathematical models are required to offer a theoretical basis for designing underwater and land-driven robotic structures. In bionic engineering science, several motion characteristics and swimming mechanisms of aquatic organisms have not been fully explored, such as the effect of dynamic instability on swimming efficiency and the drag reduction function of aquatic organisms (Li et al. 2021). Thus, there remains a big gap between most underwater bionic robots and their prototypes. Enhancing the driving efficiency of wave motion and oscillation motion is one of the crucial problems in solving bionic wave motion, but so far, this problem has not been well solved. Thus, investigating the motion characteristics and swimming mechanism of the bionic prototype and applying it to the bionic system, exploring the hydrodynamic factors in the swimming process, and improving the bionic similarity are the key issues to achieving efficient swimming of the model (Serhat, 2022).

3.4.2 Bionic water jet soft drive

Aquatic cephalopods such as squid and jellyfish can control the contraction and expansion of the cavity through muscle fibers during swimming, and their movement is in an unstable state of acceleration and deceleration (Zhou et al. 2014). At the same time, they are propelled by forces in the opposite direction of the water jet, which enables mollusks such as jellyfish to move axially at extremely high instantaneous speeds and precisely position themselves in slow motion. However, the expansion and contraction of the cavity are not completed, and the air is slowly sucked in and out, leading to discontinuous propulsion and poor movement continuity. From the above theories, the research group of the Liquid Metal Laboratory of the Institute of Physics and Chemistry of the Chinese Academy of Sciences explored the motion characteristics of jellyfish expansion and water absorption, systematically discussed the theory and technology of the liquid metal robot jellyfish integrating the interaction of a fully flexible electromagnetic coil and a magnet for the first time, and designed a bionic robot jellyfish with more natural motion and propulsion (Zhou et al. 2018) called RoMan-III. This is driven by a completely soft electromagnetic actuator, which can realize a variety of soft swimming in response to different electrical signals. Based on further conceptual experiments and computational fluid dynamics simulations, Waseda University in Japan systematically explained the response mechanism of the robot jellyfish and various factors controlling its movement behavior, including the formation of vortices and the way of rising, diving, and levitation, and developed a bionic jellyfish with a spherical structure that can float better (Francis et al. 2002). By experiment, it was found that this structure can complete the retractable movement of jellyfish more smoothly.

The squid water jet propulsion process principle is as follows: First, the squid outer box membrane expands to form negative pressure, and water fills the chamber. Second, the mantle shrinks sharply after the water jet and funnel are closed. Finally, the air is rapidly ejected from the nozzle, and the body is subjected to a force in the opposite direction of the airflow. The compressed shell of the stingray robotic fish, developed at Nanjing University, is made of photosensitive resin, and the pectoral fin skeleton is composed of 12 carbon fiber rods. The robotic fish uses a thin rubber film to squeeze the water around it as it swims to generate thrust. The oscillation of fin rays causes the fluctuation of pectoral fins, and by controlling the amplitude, frequency, and phase difference between adjacent fins, different harmonic waveforms can be produced (Wang et al. 2014b) (Fig. 12a). In Fig. 12b, the bull nose fish robot simulates the pleural motion and deformation of the bull nose rays. Each side of its internal skeleton comprises three fin-like rays, which are evenly distributed at the base of the fins along the chord. These fins play a significant role in propulsion. The tail fin functions like a lifting rudder, producing power by beating the current to help the pectoral fin float and dive (Cai et al. 2019).

California Institute of Technology established a piston jet model by studying the propulsion mechanism of a squid water jet (Wu et al. 2019) that used dynamic grid technology to simulate the formation process of vortex rings under different spindle ratios and backgrounds. The reasons for the formation of vortex rings were analyzed, and the consistency of simulation and experimental results was effectively confirmed. Harbin Institute of Technology developed a water film and bionic nozzle based on a cuttlefish jet system (Tian et al. 2022b). The bending performance of the bionic nozzle was tested at different water temperatures and driving pulse

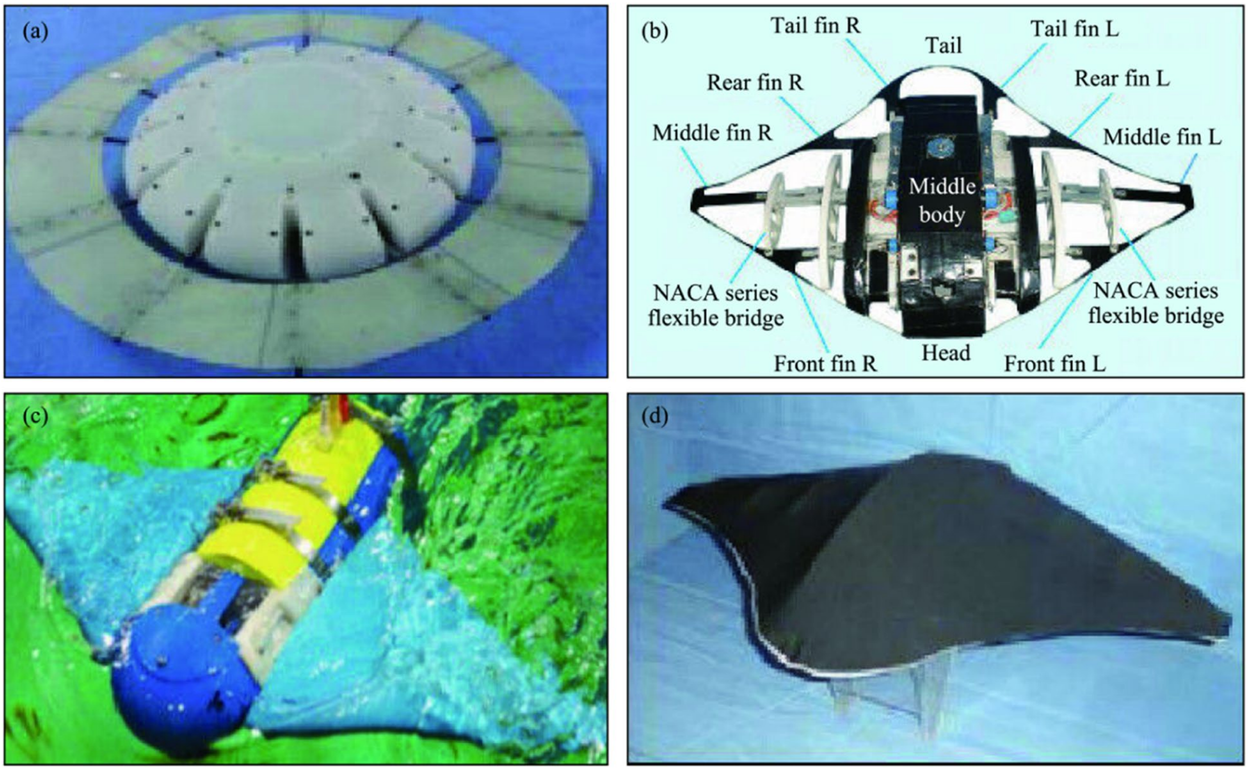

Fig. 12 Water spraying manta ray robot. **a** Robotic stingray design (Wang et al. 2014b); **b** Ox nose fish robot (Cai et al. 2019); **c** Robo-Ray IIs (Kapetanovic et al. 2020); **d** Underwater robot with elastic skin (Ma et al. 2015)

conditions. Researchers used force sensors and high-definition cameras to capture and record the movement of the bionic jet system, effectively confirming the performance characteristics of the bionic jet system (Wang et al. 2017). A new bionic manta ray robot was developed by Beihang University. The real flexible deformation of pectoral fins can be well simulated by integrating flexible mechanisms and rigid support into the mechanical structure design of the robot. Second, the CPG control method is used to realize that the controller drives the rhythmic bionic movement, and the flapping wing shoots water to push the body forward and up and down (Kapetanovic et al. 2020) (Fig. 12c). The bionic pectoral fin of the manta ray robot developed by Beihang University can produce an effective angle of attack, and the thrust generated by the interaction with the current can effectively propel the robot fish. The experimental results exhibit that the maximum forward speed of the robot fish can reach 0.43 m/s (0.94 times body length/second) when it is swimming in the tank, and it has good small radius turning maneuverability (Ma et al. 2015) (Fig. 12d).

Due to different conditions, various bionic water jet propulsion systems cannot realize the same movement as real organisms, nor do they have extremely sensitive responses and fast movement ability. However, research on biomimetic water jet propulsion systems is still in its nascent stage: there is no relatively mature biomimetic propulsion system, the types of technologies are relatively small, there are several difficulties to be overcome, and there is a long way to go.

4 Applications

Oceans are vital to life on Earth; they are key to regulating climate and balancing various ecosystems (Park and Kim 2016). They are also home to countless creatures and diverse environments. In addition, the oceans are important channels for global transportation. They are indispensable sources of energy. Despite their vital significance, oceans remain underexplored due to their harsh conditions, making exploration impossible with traditional methods. Using underwater vehicles for ocean exploration is becoming increasingly popular as they allow people to conduct safe exploration in extreme environments for long periods. At present, underwater bionic robots are used in many fields, from oil and gas and fisheries to archaeology, search, rescue, and defense (Li et al. 2014c). In addition, underwater robots are of use in scientific missions, such as mapping water composition and environmental parameters over time and space, exploring the characteristics of the seafloor in terms of depth, morphology, and composition, investigating glacial areas and icebergs, observing biological species in the environment, collecting biological and geological samples, searching for life in the deep ocean, and helping protect the environment from pollution.

4.1 Application status of underwater robots

Since the second half of the twentieth century, underwater robots have begun to assist human exploration of the ocean, and with the continuous advancement of human reach and exploration depth, underwater robots performing various tasks have also been born. In 2017, Professor Yang Canjun of Zhejiang University designed an underwater robot that can automatically clean marine life 100 m below the surface of water. In its first sea test, the robot sent back a ’selfie’ video underwater: firmly attached to the wall of the tube, spraying water filled with bubbles, and the accumulated shells were ’swept’ away. The robot is specially designed to clean the marine organisms attached to the surface of a steel pipe of an oil drilling platform and has been successfully tested in the Pinghu oil and gas field in the East China Sea. In 2018, the underwater unmanned robot enterprise Yoken Robot launched a new product—BW Space Pro—which is the world’s first underwater UAV with intelligent functions, which is widely used in diving entertainment, underwater shooting, underwater survey, sea fishing, marine environmental protection, marine biological research, aquaculture, underwater archaeology, underwater search and rescue, and other fields. In 2019, Dr. Erik Engeberg of Florida Atlantic University in the United States developed a jellyfish robot that can autonomically shuttle between coral reefs and monitor jellyfish robots at close range. Besides assisting in research, the jellyfish robot can shoulder the task of defending the ocean and serve as a small spearhead in the front line of protecting the environment. In July 2020, the team of Professor Wen Li of Beijing University of Aeronautics and Astronautics and Junzhi, a researcher from the Institute of Automation of the Chinese Academy of Sciences, designed and manufactured an underwater soft robot arm that can be applied to the natural environment of the near shallow sea, with the aim of establishing the kinematic model and rapid solution method of inverse kinematics to realize real-time kinematic control and finally realizing underwater grasp operations in the natural environment of the near shallow sea. With the upgrading and mature application of underwater robot technology, it can not only greatly reduce the risk of manual operation but also improve operation efficiency and reduce the corresponding expenditure cost. Meanwhile, driven by the integration of other innovative technologies, both the comprehensive performance and cost performance levels of underwater robots are continuing to improve, which can better complete the work and is conducive to promoting large-scale development of the industry.

4.2 Natural resource surveys

By duplicating the form of marine organisms, bionic robots can better adapt to harsh environments, such as high pressure, low temperature, and current, at the bottom of the sea. They are usually small in size and light in weight; thus, they can better collect various substances in their original conditions, which is of great significance for the study of natural resources at the bottom of the sea.

Underwater vehicles have been widely used in various marine geoscience research, initially focusing on seafloor mapping but more recently expanding to water column and oceanographic surveys. The first underwater vehicle dedicated to marine was probably the IFREMER AUV, which was used in the early 1980s to map deep-sea manganese nodule fields. A Woods Hole Oceanographic Institution (WHOI) Sentry AUV was used to map the Deepwater Horizon oil spill in the Gulf of Mexico, which resulted in a hydrocarbon plume (Levshonkov et al. 2020), using robots carrying detectors to assess its impact on animals and habitats. Many underwater vehicles were deployed in 1995 and 1996 at the Juan de Fuca Ridge in the northwestern United States to detect and map new lava flows (Stenius et al. 2022). To use magnetometers to measure young lava flows at 2200 m east longitude, WHOI developed the mixed-material underwater vehicle Nereus for scientific exploration at 11000 m in the deepest part of the ocean. This was almost twice the depth range of the AUV at the time. In 2013, the French National Center for Marine Exploitation built Orca, an unmanned cable-free underwater vehicle with a maximum depth of 6000 m (Gao et al. 2013). In 2020, the French National Sea Bomb Development Center cooperated with a company to jointly develop the ’Eret’ acoustic remote-control diving robot, which is used for underwater drilling rig inspection, submarine oil rig installation, oil pipeline auxiliary installation, anchor cable reinforcement, and other complex operations. In China, the underwater vehicle was first used in 2022 for subglacial surveys in the Arctic Ocean. Shortly after the scientific survey ship ’Ocean’ began the third leg of the expedition, ’Ocean’ conducted its first underwater robot operation in the East Pacific Sea for the first time with the underwater robot ’Sea Dragon 2’, which was used to observe a rare giant chimney in the ’Bird’s nest’ black chimney area and carried a robotic arm used to accurately capture about 7 kg of vulcanized black chimney ventilation samples. ’Hailong 2’ relying on accurate dynamic positioning, accurately landed on the seabed in the black chimney area of the ’Bird’s nest’ and performed camera observation and measurement of hydrothermal environmental parameters. The discovery marks China as one of the few countries worldwide that can use underwater robots to conduct hydrothermal surveys and sampling studies at mid-ocean ridges. The robot fish has the concealment of integrating into the fish, which can be used to collect information on the fish or guide the fish to schedule the distribution or cluster of the fish according to some algorithms (Marras and Porfiri 2012) (Fig. 13a). Thus, underwater bionic robots may effectively be used in marine environment observation, deep-sea resource exploration and development, and deep-sea and polar scientific investigation.

4.3 Biodiversity research

Through the bionic robot's similarity in appearance to marine life, marine life can be studied without disturbing its normal activities, enabling close observation of marine life and potentially becoming a new platform for studying and interacting with underwater species (Wang et al. 2020). Underwater bionic robots play an important role in marine ecological protection. First, they can be used to collect marine environmental data. Using underwater robots, scientists can obtain detailed geographic images of the ocean and the conditions at the bottom of the ocean. This data is crucial for understanding the health and pollution levels of marine ecosystems. Professor Li Tiefeng's team at Zhejiang University began research on a bionic deep-sea soft robot based on lionfish. Based on the dispersion and fusion of lionfish head bones in soft tissues, the project team performed the mechanical design of the structure and material of electronic devices and soft matrix and optimized the stress state in the robot body under a high-pressure environment. By designing materials and structures that adjust the devices and software, the robot could withstand a deep-sea pressure of 10000 m without a pressure-resistant shell and successfully conducted exploration missions in the Mariana Trench (Li et al. 2021) (Fig. 13b). Underwater robots can also be used to monitor the population and activity areas of marine life. With cameras and sensors, scientists can observe and record the behavior of

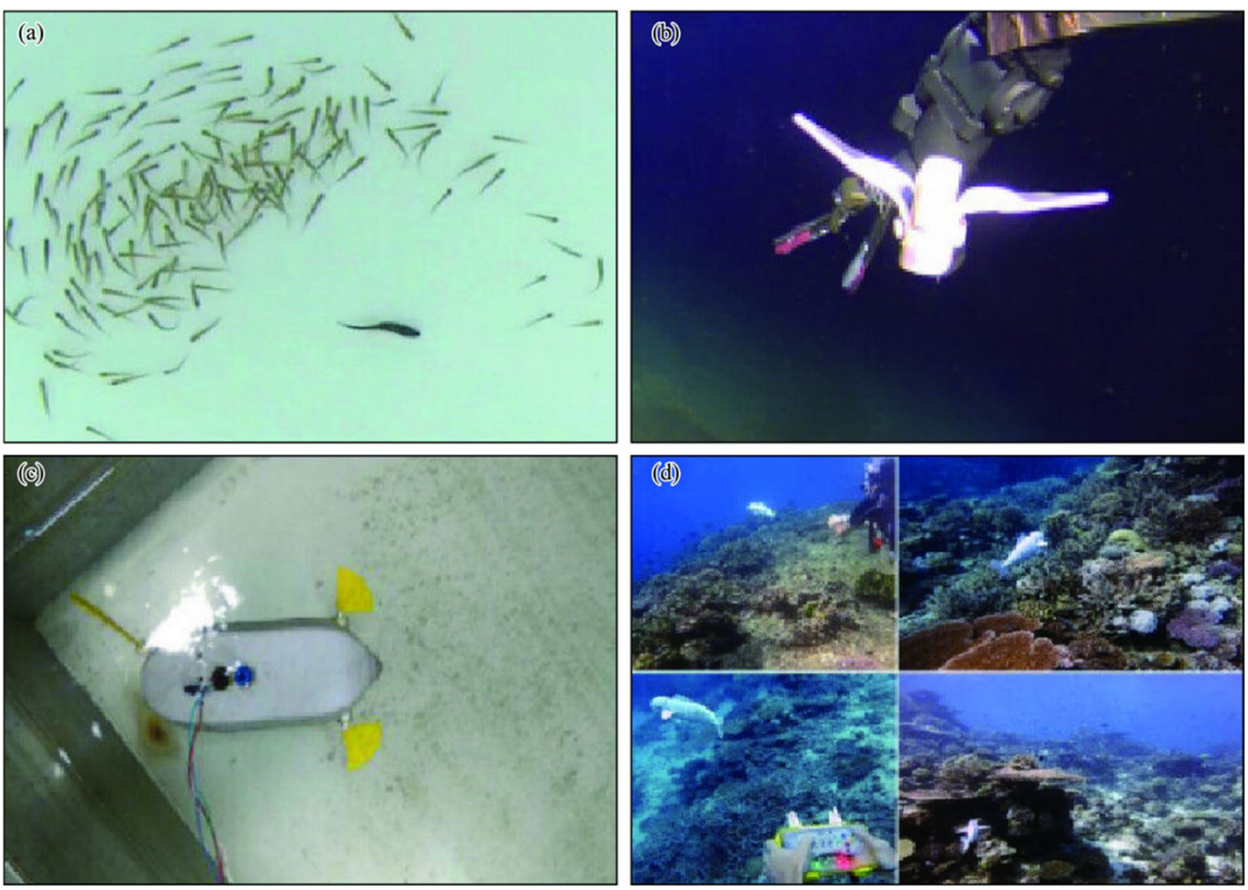

Fig. 13 Application of voice-activated soft machine fish. **a** Robot fish collect information about shoals of fish (Marras and Porfiri 2012); **b** Deep-sea exploration (Li et al. 2021); **c** Underwater positioning (Wang et al. 2020); **d** Underwater imaging (Katzschmann et al. 2018)

many aquatic organisms in real time, providing evidence for their conservation.

In addition to data collection and monitoring, ROV maps can help protect marine life. They can remove debris and harmful substances from the ocean. Many marine creatures often die by ingesting waste. The underwater vehicle can collect this waste through its robotic arm and bring it to a safe location for disposal. Some underwater robot maps can even perform deep seabed cleanup operations to help restore the health of the ocean (Wang et al. 2002) (Fig. 13c). The University of Icahnx developed a new kind of robotic fish for detecting pollution in river water and drawing 3D pollution maps of the river (Gomatam et al. 2012). Each robotic fish is about 50 cm long, 15 cm high, and 12 cm wide. Each is equipped with pollution detection sensors and Global Positioning System (GPS), can 'smell' harmful substances in the water, and can work together, even if there is no one to direct. When they 'sniff out' the harmful substances in the water, they communicate with each other through a Wi-Fi wireless connection. The GPS navigation system allows them to swim freely without human operation, and once they find pollutants, they will send an alert to the environmental protection department personnel (Skorohod et al. 2020).

Biosensors were first deployed on an underwater robot when an NERC autonomous submersible AUV was fitted with an in situ dissolved manganese analyzer (Skorohod et al. 2020). This deployment showed how an autonomous underwater robot carrying a biosensor could detect small-scale changes in species distribution that traditional sampling methods could not address. Since then, chemical sensors on underwater robots used for marine purposes have been used mainly to search the water column for active hydrothermal columns and to study species distributions, and a suite of sensors for detecting hazardous liquid spills have been deployed on underwater robots in the North Sea Sleipner project for frequent, high time scale studies of areas of potential spills to protect the ecological environment (Tran and Park 2020). By application of underwater robot mapping, people can better protect the diversity of marine ecosystems and marine life. They help people understand and solve the problems of the marine environment and provide a guarantee for the rational use of marine resources.

4.4 Underwater imaging

There is an increasing demand for exploration of the seabed environment, and the imaging requirements for marine resources and the underwater world are also getting higher and higher (Liang et al. 2010). Due to the uncertainty of the underwater environment, such as interference of the current and limited sensing ability, conventional underwater navigation equipment has limitations; thus, bionic robots designed for different underwater environments have great advantages.

The bionic underwater foot robot studied by the National Metrology Institute of Japan (Maeda et al. 2020) imitates the appearance and behavior of crabs and can walk and jump underwater. Compared to traditional AUV and ROV, it is better adapted to complex underwater terrains and has a higher affinity for underwater organisms. Due to their bionic appearance, the natural movements of underwater creatures can be well imaged. National Institute of Ocean Technology (Ramesh et al. 2017) used the bionic fish REMUS to map the habitat at 1–2 m water depth in the Juan Strait in the northern United States. It used underwater video data for ground truth measurements. Underwater robots have been used to map various seafloor morphological features, including under ice sheets inaccessible to research ships. For instance, State Marine Technical University (Siek and Sakovich 2019) used the underwater vehicle NERC Autosub3 to investigate the retreat of the Pine Island Glacier (PIG) in West Antarctica. The robot performed six missions in 94 h, collecting 510 km of orbital data under the PIG ice shelf 50 km above the ice surface.

Underwater vehicles are also being used to image sedimentary features in submarine canyons. The University of Kanagawa used an underwater vehicle carrying a high-resolution multibeam waveform acoustic system (0.7 m lateral resolution) and a submarine profiler (0.1 m vertical resolution) to conduct underwater imaging experiments, collecting data from La Jolla Canyon on the Southern California coast. To understand the processes that produce observational patterns on a scale comparable to the surface (Tsukioka et al. 2002), the Science and Technology on Underwater Vehicle Laboratory used underwater robotic fish diving to collect deep-sea data and provide vibration core samples for sediment dating (Liu et al. 2020) (Fig. 13d). In the article on acoustically controlled soft robotic fish studied by the University of Zagreb (Kapetanovic et al. 2020), it is possible to approach underwater organisms without disturbing their normal life and to image underwater organisms and underwater landscapes through shape features similar to those of fish (Katzschmann et al. 2018).

When conducting underwater imaging, conventional underwater vehicles have higher accuracy in the tangential direction of the seabed and lower accuracy in the vertical direction of the seabed. In comparison, underwater bionic robots have lower accuracy in the tangential direction of the seabed and higher accuracy in the vertical direction of the seabed (Wang et al. 2014a). Moreover, the underwater bionic robot has high stability and adaptability to the seabed environment, and the combination of the two can obtain higher-quality underwater imaging maps.

4.5 Underwater search and rescue

Underwater robots can be used to check whether explosives are installed on dams and bridge piers, remote-reconnaissance structural conditions or dangerous goods, and closely inspect underwater evidence. In 2010, underwater robots could walk at 3–6 km/h in the deepest underwater world of 6000 m (Brown and Clark 2010). The forward-looking and downward-looking radar gives it 'good eyesight'. The accompanying camera, video camera, and precise navigation system allow it to 'overlook'. The underwater robot WHOI provided in 2012 took just a few days to find the wreckage of an Air France flight in 4000 km^2 of ocean after two years of fruitless searching by various ships and aircraft. Underwater robots have great potential and application value in rescue missions. When encountering dangerous situations, underwater bionic robots can play a greater role in on-site situation assessment and positioning, providing important information for the next step. Through the underwater high-definition camera group, sonar, and a variety of sensors carried by the underwater robot itself, rescue workers can grasp the water depth and temperature on the shore. They can determine the obstacles in the water and remove the danger of entering the water (Wang et al. 2019c). In salvage and other operations, the underwater robot can quickly locate the location of underwater objects. Armed with this information, commanders can better formulate a reasonable and efficient rescue plan. Another major advantage of underwater robots lies in search and rescue missions. In dangerous waters such as rapids and low temperatures, it can take the lead in entering underwater areas that rescuers cannot reach to detect the location and situation of trapped people. The robot operator can control the movement of the robot by manipulating the handle or wireless sensing device on the shore. Carrying tools such as robotic arms can also assist rescue workers in completing tasks such as clearing and salvaging. The water environment where the danger occurs is not always ideal, and low visibility is one of the most significant problems. Bionic fluorescent robot fish can provide rescuers with a light source, and rescuers can also determine the location of the target and search for risks by referring to the umbilical cable connected to the underwater robot (Asadnia et al. 2015). The emergence of underwater robots makes underwater rescue work safer and more efficient.

5 Summary and outlook

From the above summarized research results, it can be observed that research on bionic underwater robots has grown considerably. Rapid turning, path tracking, autonomous operation, and other actions have been achieved on some prototypes, and there is a great improvement in speed and mobility, but there is still a very obvious gap with real fish. Underwater bionic robot development is high-end manufacturing industry supported by the Chinese government and plays the role of a 'strategic commanding height'. In China and abroad, a series of work has been conducted on the mechanical structure design, materials, and control methods of underwater bionic robots, and the related research has grown considerably. Due to the complexity of underwater, the mechanical structure design and control technology of underwater robots still require further optimization and improvement to truly achieve a life-like system that integrates the structure and biological characteristics. By enhancing the characteristics of underwater robots, such as self-control and self-perception, and through the coordinated control of robot systems, underwater robots can better integrate into the underwater environment to complete the work, pursue sustainability on the road to development, and make this technology more mature.

Research on bionic underwater robots has become more in-depth and expanded, and some prototypes have realized multimodal motion, fast turning, path tracking, autonomous operation, and other actions, which have greatly improved in speed and maneuverability. However, there is still a very obvious gap with real fish. In the future, bionic underwater robots should be developed into autonomous, intelligent, and collaborative tools. To further improve the performance of the bionic underwater robot system, further work should be conducted in the following main research directions: (1) Mechanism design and optimization. Most bionic underwater robots are driven by motors. Research can be conducted in terms of streamlined low-resistance shapes, intelligent driving materials, and rigid and flexible coupling efficient transmission mechanisms to improve the motion performance of bionic underwater robots. (2) Underwater environment perception and modeling are significant for bionic underwater robots to perform underwater tasks. Information fusion technology of various sensors can be examined and combined with the technology to conduct underwater environment modeling and improve the autonomy intelligence of bionic underwater robots. (3) Intelligent control methods, such as artificial intelligence, are a hot field right now. Some artificial intelligence technologies, such as reinforcement learning and transfer learning, can be applied to the intelligent control of bionic underwater robots so that they can learn various motor skills independently. (4) Multibionic underwater robot cooperation. In nature, fish is often in the form of clusters for foraging, defense, and cruising. The use of multiple bionic underwater vehicles to form a cooperative system is helpful in improving operational efficiency. Due to the complexity of underwater, the particularity of the propulsion mechanism, and the bottleneck of underwater communication, sensing, positioning, and other technologies, the collaboration of multibionic underwater robots will be a very challenging direction.

Due to the complexity of the marine environment, underwater bionic robots will face problems such as the drastic change in water velocity, the difference in pressure under different water depths, and their waterproofing, which poses a great challenge to the structural design of robots. To address these issues, the structure of the future underwater bionic robot needs to be more detailed and more lightweight, and the application of materials should also meet the requirements of the underwater environment. Miniaturization is the current trend of robot development because small structures are easier to adapt to the environment, reduce the contact area, and thus reduce the impact of underwater pressure on the machine structure to a greater extent. The most prominent point is that miniaturized robots are closer to the physiological structure of marine organisms and fundamentally realize the bionic effect rather than just the imitation of appearance. Marine space is generally unsuitable for human survival, and large-scale development and utilization of marine resources have a great dependence on robotics technology. Replacing humans with robots to promote and realize unmanned marine equipment has far-reaching strategic significance. Thus, future bionic underwater robots should be further developed, mainly in the direction of autonomy, intelligence, and synergy, to enhance the performance of bionic underwater robotic systems.

Acknowledgements
This work was supported by grants from the National Natural Science Foundation of China (Grant Nos. 62201537 and U20A20194), the Natural Science Foundation of Shandong Province (Grant No. ZR2022QF008), and the Central University Basic Research Fund of China (Grant No. 202312035). We thank Yanyue Teng at the Ocean University of China for the useful discussion on the soft actuator drive part of this review.

Authors' contributions
Zhongao Cui and Liao Li performed the literature survey, drafted the manuscript and revised it critically for the key content. Yuhang Wang conducted literature research and content verification. Zhiwei Zhong carried out the document sorting and figure modification. Junyang Li is the corresponding author, responsible for organizing the manuscript sequence alignment, proofreading and revising the manuscript, and giving the final approval of the version to be published. All authors read and approved the final manuscript.

Availability of data and materials
The data and materials used to support the findings of this study are included in the article.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The author declares that there are no conflicts of interest regarding the publication of this paper.

Received: 24 August 2023 Revised: 12 September 2023 Accepted: 14 September 2023
Published online: 18 October 2023

References
Alexander P (2017) Robot fish: bio-inspired fishlike underwater robots. Underwater Technol Int J Soc Underwater 34(3):143–145
Asadnia M, Kottapalli AGP, Haghighi R, Cloitre A, Alvarado PV, Miao JM et al (2015) MEMS sensors for assessing flow-related control of an underwater biomimetic robotic stingray. Bioinspir Biomim 10(3):10
Ay M, Korkmaz D, Koca GO, Bal C, Akpolat ZH, Bingol MC (2018) Mechatronic design and manufacturing of the intelligent robotic fish for bio-inspired swimming modes. Electronics 7(7):118
Bai XJ, Wang Y, Wang S, Wang R, Tan M, Wang W (2021) Modeling and analysis of an underwater biomimetic vehicle-manipulator system. Sci China Inf Sci 65(3):35
Bal C, Koca GO, Korkmaz D, Akpolat ZH, Ay M (2019) CPG-based autonomous swimming control for multi-tasks of a biomimetic robotic fish. Ocean Eng 189:106334
Bottasso CL, Scorcelletti F, Ruzzene M, Ahn SS (2008) Trajectory optimization for DDE models of supercavitating underwater vehicles. J Dyn Syst Meas Control 131(1):18
Brown C, Clark RP (2010) Automated conceptual design utility for unmanned underwater vehicles. Sea Technol 51(12):33–36
Cai YR, Bi SS, Li GY, Hildre HP, Zhang HX (2019) From natural complexity to biomimetic simplification: the realization of bionic fish inspired by the Cownose Ray. IEEE Robot Autom Mag 26(3):27–38
Cao Q, Wang R, Zhang T, Wang Y, Wang S (2022) Hydrodynamic modeling and parameter identification of a bionic underwater vehicle: RobDact. Cyborg Bionic Syst 2022:13
Chen AL, Thind K, Demir KG, Gu GX (2021a) Modeling bioinspired fish scale designs via a geometric and numerical approach. Materials 14(18):5378
Chen BX, Jiang HZ (2019) Swimming performance of a tensegrity robotic fish. Soft Rob 6(4):520–531
Chen JY, Yin B, Wang CC, Xie FR, Du RX, Zhong Y (2021b) Bioinspired closed-loop CPG-based control of a robot fish for obstacle avoidance and direction tracking. J Bionic Eng 18(1):171–183
Chen X, Shigemune H, Sawada H (2020) An untethered bionic robotic fish using SMA actuators. Int Conf Mechatr Auto 13(6):1768–1773
Chen X, Wu Z, Yu J, Zhou C, Yu JZ (2017) Design and implementation of a magnetically actuated miniature robotic fish. 20th World Congress of the International-Federation-of-Automatic-Control (IFAC), Toulouse, France, 9-14 July 2017, pp 6851–6856
Chong CW, Zhong Y, Zhou CL, Low KH, Seet GLG, Lim HB (2009) Can the swimming thrust of BCF biomimetics fish be enhanced. 2008 IEEE International Conference on Robotics and Biomimetics, Bangkok, Thailand, 22-25 February 2009, pp 437–442
Chowdhury AR, Prasad B, Kumar V, Kumar R, Panda SK (2011) Design, modeling and open-loop control of a BCF mode bio-mimetic robotic fish. Int Siberian Conf Contr Commun 15(3):87–93
Chu WS, Lee KT, Song SH, Han MW, Lee JY, Kim HS et al (2012) Review of biomimetic underwater robots using smart actuators. Int J Precis Eng Manuf 13:1281–1292
Crespi A, Ijspeert AJ (2008) Online optimization of swimming and crawling in an amphibious snake robot. IEEE Trans Rob 24(1):75–87

Dawson HA, Allison M (2020) Requirements for Autonomous Underwater Vehicles (AUVs) for scientific data collection in the Laurentian Great Lakes: a questionnaire survey. J Gt Lakes Res 47(1):259–265
Du T, Hughes J, Wah S, Matusik W, Rus D (2021) Underwater soft robot modeling and control with differentiable simulation. IEEE Robot Auto Lett 6(3):4994–5001
Francis O, Coakley G, Kitts C (2002) A digital control system for the triton undersea robot. IFAC Proc Vol 35(2):633–638
Fras J, Noh Y, Macias M, Wurdemann H, Althoefer K (2018) Bio-inspired octopus robot based on novel soft fluidic actuator. IEEE Int Conf Robot Auto 21(5):1583–1588
Gao CZ, Du YC, Yang L (2022) The influence of the discharge port structure on the infrared characteristics of underwater vehicle thermal jets. Appl Sci 12(14):7108
Gao JW, Yu JP, Li QC, Leng WZ, Ma ZT (2013) A layered obstacles avoidance algorithm for biomimetic robotic fish. ICIC Express Letters 7(1):1798–1810
Gomatam S, Vengadesan S, Bhattacharyya SK (2012) Numerical simulations of flow past an autonomous underwater vehicle at various drift angles. J Nav Archit Mar Eng 9(2012):135–152
Guo S, He Y, Shi L, Pan S, Xiao R, Tang K et al (2018) Modeling and experimental evaluation of an improved amphibious robot with compact structure. Robot Comp-Integr Manufact 51(2):37–52
Guo SX, Shi LW, Ye XF, Li LF (2007) A new jellyfish type of underwater microrobot. 2007 International Conference on Mechatronics and Automation, Harbin, pp 509–514
Haji BJ, Bamdad M (2022) Nonlinear modeling and analysis of a novel robot fish with compliant fluidic actuator as a tail. J Bionic Eng 19(3):629–642
Hu Q, Dong E, Cheng G, Jin H, Yang J, Sun D (2019) Inchworm-inspired soft climbing robot using microspine arrays. IEEE/RSJ Int Conf Intell Robots Syst (IROS) 78(5):5800–5805
Hu QQ, Dong EB, Sun D (2023) Soft modular climbing robots. IEEE Trans Robot 39(1):399–416
Hu QS, Zhou H (2009) IPMC propelled biomimetics robotic fish energy consumption model construction and its application to energy-saving control. IEEE International Conference on Robotics and Biomimetics (ROBIO), Guilin, China, 19-23 December 2009, pp 2151–2156
Jiao ZW, Wang HY, Luo B, Yang WM, Yu Y (2022) A BCF bionic robot fish driven by a dielectric elastomer actuator. J Phys: Conf Ser 2331(1):12010
Jung KY, Kim, IS, Yang SY, Lee MH (2002) Autopilot design of an autonomous underwater vehicle using robust control. Int J Control Autom Syst 4(4):264–269
Kapetanovic N, Vasilijevic A, Nad D, Zubcic K, Miskovic N (2020) Marine robots mapping the present and the past: unraveling the secrets of the deep. Remote Sens 12(23):3902
Karthik S (2014) Underwater vehicle for surveillance with navigation and swarm network communication. Indian J Sci Technol 7(S6):22–31
Katzschmann RK, DelPreto J, MacCurdy R, Rus DL (2018) Exploration of underwater life with an acoustically controlled soft robotic fish. Sci Robot 3(1):12–22
Kelasidi E, Pettersen KY, Liljeback P, Gravdahl JT (2016) Locomotion efficiency of underwater snake robots with thrusters. 14th IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR), Lausanne, Switzerland, 23-27 October 2016, pp 174–181
Khalaji AK, Zahedifar R (2020) Lyapunov-based formation control of underwater robots. Robotica 38(6):1105–1122
Ko Y, Na S, Lee Y, Cha K, Ko SY, Park J et al (2012) A jellyfish-like swimming mini-robot actuated by an electromagnetic actuation system. Smart Mater Struct 21(5):057001
Koch RM (2002) Analysis of variable-thickness, streamlined transducer array windowing concepts for high speed underwater vehicles. J Acoust Soc Am 112(5):2217–2218
Kopman V, Porfiri M (2013) Design, modeling, and characterization of a miniature robotic fish for research and education in biomimetics and bioinspiration. IEEE/ASME Trans Mechatron 18(2):471–483
Korkmaz D, Akpolat ZH, Soyguder S, Alli H (2015) Dynamic simulation model of a biomimetic robotic fish with multi-joint propulsion mechanism. Trans Inst Meas Contr 37(5):684–695
Korkmaz D, Budak U, Bal C, Koca GO, Akpolat Z (2012) Modeling and implementation of a biomimetic robotic fish. Int Symp Power Electr Power Electr Electr Drives, Automat Motion 77(5):1187–1192
Kumar S, Rastogi V, Gupta P (2016) Recent developments in modeling and control of underwater robot manipulator: a review. Indian J Sci Technol 9(48):8
Levshonkov NV, Gusev AL, Krylosova AA (2020) Calculation of vibrations in a tethered underwater vehicle-umbilical cable system. J Mach Manuf Reliab 49(7):562–567
Li DJ (2015) Analysis on numerical simulation for bionic robot fish based on CATIA. Appl Mech Mat 742:511–515
Li G, Chen X, Zhou F, Liang Y, Xiao Y, Cao X et al (2021) Self-powered soft robot in the Mariana trench. Nature 591(7848):66–71
Li J, Zhang YX, Li WB (2021) Formation control of a multi-autonomous underwater vehicle event-triggered mechanism based on the Hungarian algorithm. Machines 9(12):346
Li L, Wang C, Xie GM (2014a) Modeling of a carangiform-like robotic fish for both forward and backward swimming: based on the fixed point. IEEE International Conference on Robotics and Automation (ICRA), Hong Kong, pp 800–805
Li T, Li G, Liang Y, Cheng T, Dai J, Yang X et al (2017) Fast-moving soft electronic fish. Sci Adv 4(1):7
Li WK, Chen H, Cui WC, Song CH, Chen LK (2023) Multi-objective evolutionary design of central pattern generator network for biomimetic robotic fish. Complex Intell Syst 9:1707–1727
Li Y, Jiang YQ (2012) The application of distributed multi-sensor information fusion technology in underwater vehicle. Adv Mat Res 532–533:1006–1010
Li Y, Jiang YQ, Ma S, Chen PY, Li YM (2014b) Inverse speed analysis and low speed control of underwater vehicle. J Centr South Univ 21(7):2652–2659
Li YS, Sun HX, Chu M, Zhang YH, Jia QX, Lan XJ (2014c) Experiment, simulation and analysis on coupling hydrodynamic forces under key parameters for a spherical underwater exploration robot. J Vibroengine 16(6):3014–3025
Li ZG, Ge LM, Xu WQ, Du YJ (2018) Turning characteristics of biomimetic robotic fish driven by two degrees of freedom of pectoral fins and flexible body/caudal fin. Int J Adv Rob Syst 15(1):21
Li ZJ, Yin PL, Jiang XM, Tang LH, Wu H, Peng Y et al (2021) Towards self-powered technique in underwater robots via a high-efficiency electromagnetic transducer with circularly abrupt magnetic flux density change. Appl Energy 302(4):793–798
Liang JH, Wang TM, Wen L (2011) Development of a two-joint robotic fish for real-world exploration. J Field Robot 28(1):70–79
Liang XA, Zhang JD, Li W, Su LF (2010) Extended Kalman filter based identification of dynamic model for underwater robots. International Conference on Applied Mechanics and Mechanical Engineering, Changsha, China, 8-9 September 2010, pp 780–783
Liu G, Wang M, Xu L, Incecik A, Sotelo MA, Li Z et al (2020) A new bionic lateral line system applied to pitch motion parameters perception for autonomous underwater vehicles. Appl Ocean Res 99:102142
Liu J, Hu H (2010) Biological inspiration: from carangiform fish to multi-joint robotic fish. J Bionic Eng 7(1):35–48
Liu JD, Hu HS (2006) Biologically inspired behaviour design for autonomous robotic fish. Int J Autom Comput 3(4):336–347
Liu YW, Jiang HZ (2022) Research development on fish swimming. Chin J Mech Engine 35(1):114
Lou BD, Ni YJ, Mao MH, Wang P, Cong Y (2017) Optimization of the kinematic model for biomimetic robotic fish with rigid headshaking mitigation. Robotics 6(4):30
Low KH (2009) Modelling and parametric study of modular undulating fin rays for fish robots. Mech Mach Theory 44(3):615–632
Ma HW, Cai YR, Wang YL, Bi SS, Gong Z (2015) A biomimetic cownose ray robot fish with oscillating and chordwise twisting flexible pectoral fins. Industr Robot: Int J 42(3):214–221
Ma LP, Yue ZJ, Zhang RF (2020) Path tracking control of hybrid-driven robotic fish based on deep reinforcement learning. 2020 IEEE International Conference on Mechatronics and Automation (ICMA), Beijing, China, 13-16 October 2020, pp 815–820
Ma YJ, Li XY, Liang B, Du Y, Liu JQ, Yang S (2019) Development and motion mode analysis of IPMC bionic jellyfish based on app bluetooth remote control. IOP Conf Ser: Earth Environ Sci 252(2):022040

Maeda Y, Kida Y, Deguchi M (2020) Hadal free-fall camera lander transmitting hadal images via high-rate acoustic communication. Sea Technol 61(12):22–24

Marchese AD, Onal CD, Rus D (2014) Autonomous soft robotic fish capable of escape maneuvers using fluidic elastomer actuators. Soft Robot 1(1):75–87

Marras S, Porfiri M (2012) Fish and robots swimming together: attraction towards the robot demands biomimetic locomotion. J R Soc Interf 9(73):1856–1868

Nagai T, Shintake J (2022) Rolled dielectric elastomer antagonistic actuators for biomimetic underwater robots. Polymers 14(21):4549

Najem J, Sarles SA, Akle B, Leo DJ (2012) Biomimetic jellyfish-inspired underwater vehicle actuated by ionic polymer metal composite actuators. Smart Mater Struct 21(9):11

Nakashima M, Karako Y (2014) Effect of bubbles around an underwater robot arm on thrust during the crawl stroke motion. Proc Engine 72(1):715–719

Ning KW, Hartono P, Sawada H (2022) Using inverse learning for controlling bionic robotic fish with SMA actuators. MRS Adv 7(30):649–655

Ozog P, Johnson-Roberson M, Eustice RM (2017) Mapping underwater ship hulls using a model-assisted bundle adjustment framework. Robot Auton Syst 87(4):329–347

Park J, Kim J (2016) Model-based pose estimation for high-precise underwater navigation using monocular vision. J Korea Robot Soc 11(4):14

Pham TH, Nguyen K, Park HC (2023) A robotic fish capable of fast underwater swimming and water leaping with high Froude number. Ocean Eng 268(1):113512

Praczyk T (2014) Using augmenting modular neural networks to evolve neuro-controllers for a team of underwater vehicles. Soft Comput Fusion Foundations Methodol Appl 18(12):2445–2460

Rajamohamed S, Raviraj P (2015) Bio-inspired swimming techniques for robotic fish using fow and pressure sensing mechanism (computational bio-mimetic). Ind J Sci Technol 8(24):10

Ramesh S, Ramadass GA, Prakash VD, Sandhya CS, Ramesh R, Sathianarayanan D et al (2017) Application of indigenously developed remotely operated vehicle for the study of driving parameters of coral reef habitat of South Andaman Islands India. Curr Sci 113(12):2353–2359

Ravalli A, Rossi C, Marrazza G (2017) Bio-inspired fish robot based on chemical sensors. Sens Actuators, B Chem 239:325–329

Ren QY, Xu JX, Fan LP, Niu XL (2013) A GIM-based biomimetic learning approach for motion generation of a multi-joint robotic fish. J Bionic Eng 10(4):423–433

Rossi C, Colorado J, Coral W, Barrientos A (2011) Bending continuous structures with SMAs: a novel robotic fish design. Bioinspir Biomim 6(4):045005

Sabet M, Nourmohammadi H (2022) Water velocity sensor with the ability to estimate the sideslip angle based on Bernoulli's law for use in autonomous underwater vehicles. Ocean Eng 263(3):112252

Şafak KK, Adams GG (2002) Dynamic modeling and hydrodynamic performance of biomimetic underwater robot locomotion. Auton Robot 13(3):233–240

Salumäe T, Kruusmaa M (2013) Flow-relative control of an underwater robot. Math Phys Engine Sci 469(2153):20120671

Sankaranarayanan V, Mahindrakar AD, Banavar RN (2008) A switched controller for an underactuated underwater vehicle. Commun Nonlinear Sci Numer Simul 13(10):2266–2278

Saxena M, Chauhan NR (2017) A review study on bio-inspired robotic fish. Int J of Mechan Robot Syst 4(1):1–23

Scaradozzi D, Palmieri G, Costa D, Pinelli A (2017) BCF swimming locomotion for autonomous underwater robots: a review and a novel solution to improve control and efficiency. Ocean Eng 130:437–453

Serhat Y (2022) Development stages of a semi-autonomous underwater vehicle experiment platform. Int J Adv Robot Syst 19(3):15

Shen Q, Olsen Z, Stalbaum T, Trabia S, Lee J, Hunt R et al (2020) Basic design of a biomimetic underwater soft robot with switchable swimming modes and programmable artificial muscles. Smart Mater Struct 29(3):1–24

Shen Q, Wang TM, Liang JH, Wen L (2013) Hydrodynamic performance of a biomimetic robotic swimmer actuated by ionic polymer–metal composite. Smart Mater Struct 22(7):075035

Shi L, Guo S, Asaka K (2010) A novel jellyfish-like biomimetic microrobot. 2010 IEEE/ICME Int Conf Compl Med Engine 13(5):277–281

Shi LW, Guo SX, Mao SL, Yue CF, Li MX, Asaka K (2013) Development of an amphibious turtle-inspired spherical mother robot. J Bionic Eng 10(4):446–455

Shintake J, Cacucciolo V, Shea H, Floreano D (2018) Soft biomimetic fish robot made of dielectric elastomer actuators. Soft Robot 5(4):466–474

Siek Y, Sakovich S (2019) Simulation of the controlled movement based on the complexity principle for an automatic underwater vehicle. Vibroeng Procedia 25:194–200

Skorohod BA, Statsenko AV, Fateev SI, Zhilyakov PV (2020) Accuracy analysis of 3D points reconstructed from workspace of underwater robot. J Phys: Conf Ser 1661(1):1–7

Song TL, Lu YP, Liu HQ (2013) Control and research of bionic robotic fish based on Arduino. Adv Mat Res 2428(706–708):691–694

Stenius I, Folkesson J, Bhat S, Sprague CI, Ling L, Özkahraman Ö et al (2022) A system for autonomous seaweed farm inspection with an underwater robot. Sensors 22(13):5064

Su ZS, Yu JZ, Tan M, Zhang JW (2014) Implementing flexible and fast turning maneuvers of a multijoint robotic fish. IEEE/ASME Trans Mechatron 19(1):329–338

Suk YT, Hwan KM (2014) Analysis of integrated navigation performance for sensor selection of Unmanned Underwater Vehicle (UUV). J Ocean Engine Technol 28(6):566–573

Tian QH, Wang T, Wang YX, Li CJ, Liu B (2022a) Robust optimization design for path planning of bionic robotic fish in the presence of ocean currents. J Marine Sci Engine 10(8):1109

Tian QH, Wang T, Wang YX, Wang ZW, Liu CW (2022b) A two-level optimization algorithm for path planning of bionic robotic fish in the three-dimensional environment with ocean currents and moving obstacles. Ocean Eng 266(P3):112829

Todd C, Samuel L, Yahya MS (2020) A bio-inspired robotic fish utilizes the snap-through buckling of its spine to generate accelerations of more than 20g. Bioinspir Biomim 15(5):1–18

Trabia S, Shen Q, Stalbaum T, Hunt R, Hwang T, Kim K (2016) Numerical and experimental investigation of a biomimetic robotic jellyfish actuated by ionic polymer-metal composite. 13th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI), Xi'an, China, 19-22 August 2016, pp 204–205

Tran LG, Park WT (2020) Biomimetic flow sensor for detecting flow rate and direction as an application for maneuvering autonomous underwater vehicle. Int J Prec Engine Manufacturing-Green Technol 9(1):163–173

Tsukioka S, Aoki T, Ochi H, Shimura T, Sawa T, Nakamura T et al (2002) Development of an acoustic lens for an imaging sonar for autonomous underwater vehicle 'Urashima' and experimentation in a water tank. Jpn J Appl Phys 41(6R):1–10

Villanueva A, Smith C, Priya S (2011) A biomimetic robotic jellyfish (Robojelly) actuated by shape memory alloy composite actuators. Bioinspir Biomim 6(3):036004

Vogel V (2012) Soft robotics: bionic jellyfish. Nat Mater 11(10):841–842

Vu MT, Jeong SK, Choi HS, Oh JY, Ji DH (2018) Study on down-cutting ladder trencher of an underwater construction robot for seabed application. Appl Ocean Res 71:90–104

Wang CC, Lu J, Ding XL, Jiang CX, Yang JY, Shen JH (2021) Design, modeling, control, and experiments for a fish-robot-based IoT platform to enable smart ocean. IEEE Int Things J 8(11):9317–9329

Wang G, Song YJ, Tang WS, Xie GM, Li DJ (2019a) A numerical simulation analysis on bionic robot fish based on Computational Fluid Dynamics (CFD) method. J Nanoelectron Optoelectron 14(3):400–407

Wang LL, Wang HJ, Pan LX (2014a) Autonomous underwater vehicle motion planning via sampling based model predictive control. Appl Mech Mater 670–671:1370–1377

Wang M, Dong HF, Li X, Zhang YL, Yu JZ (2019b) Control and optimization of a bionic robotic fish through a combination of CPG model and PSO. Neurocomputing 337:144–152

Wang M, Zhang YL, Dong HF, Yu JZ (2020) Trajectory tracking control of a bionic robotic fish based on iterative learning. Sci China Inf Sci 63(7):170202

Wang R, Wang S, Wang Y, Cai MX, Tan M (2019c) Vision-based autonomous hovering for the biomimetic underwater robot-RobCutt-II. IEEE Trans Industr Electr 66(11):8578–8588

Wang SY, Han Y, Mao ST (2021) Innovation concept model and prototype validation of robotic fish with a spatial oscillating rigid caudal fin. J Marine Sci Eng 9(4):435
Wang T, Wang Z, Zhang B (2021) Mechanism design and experiment of a bionic turtle dredging robot. Machines 9(5):86
Wang TM, Liang JH, Shen GX, Tan GK (2005) Stabilization based design and experimental research of a fish robot. IEEE/RSJ International Conference on Intelligent Robots and Systems, Edmonton, Canada, 2-6 August 2005, pp 2065–2070
Wang W, Bian XQ, Chang ZH (2002) 3D track-keeping method for autonomous underwater vehicle. J Mar Sci Appl 1(2):18–22
Wang W, Wei XY, Meng K, Zhong LH, Wang Y, Yu XH (2017) Bio-tribology properties of bionic carp scale morphology on Ti6A14V surface. IOP Conf Ser: Mat Sci Engine 281:012060
Wang YD, Wang PC (2014) Design of a kind of minitype shallow water power underwater vehicle. Appl Mechan Mat 644–650:674–677
Wang YW, Tan JB, Gu BT, Sang PF, Zhao DB (2014b) Design and modeling of a biomimetic stingray-like robotic fish. Adv Mat Res 945–949:1473–1477
Wang YW, Tan JB, Zhao DB (2015) Erratum to: 'Design and experiment on a biomimetic robotic fish inspired by freshwater stingray.' J Bionic Eng 12(3):371
Wang ZL, Wang YW, Li J, Hang GR (2009) A micro biomimetic manta ray robot fish actuated by SMA. 2009 IEEE International Conference on Robotics and Biomimetics (ROBIO), Guilin, pp 1809–1803
Wang ZW, Dong CL, Zhang ZM, Tian QH, Sun AQ, Yuan L et al (2022) Review of multi-fin propulsion and functional materials of underwater bionic robotic fish. Proc Inst Mech Eng C J Mech Eng Sci 236(13):71
Watts CM, McGookin EW (2014) Surge performance of an underwater vehicle with a biomimetic tendon drive propulsion system. Proc Inst Mech Engine, Part M: J Engine Maritime Environ 228(4):315–330
Wehner M, Truby RL, Fitzgerald DJ, Mosadegh B, Whitesides GM, Lewis JA et al (2016) An integrated design and fabrication strategy for entirely soft, autonomous robots. Nature 536(7617):451–455
Wu RX, Du G, Liu Z, Zhang DX, Yu YJ (2021a) Design of bionic robot fish propelled by two joint caudal fin. J Phys: Conf Ser, 1982:012056
Wu YH, Liu JC, Wei YG, An D, Duan YH, Li WS et al (2021b) Intelligent control method of underwater inspection robot in netcage. Aquac Res 53(5):1928–1938
Wu YH, Ta XX, Xiao RC, Wei YG, An D, Li DL (2019) Survey of underwater robot positioning navigation. Appl Ocean Res 90:101845
Wu ZX, Yu JZ, Su ZS, Tan M (2013) Control and implementation of S-start for a multijoint biomimetic robotic fish. Acta Automatica Sinica 39(11):1914–1922
Wynn RB, Huvenne VAI, Le Bas TP, Murton BJ, Connelly DP, Bett BJ et al (2014) Autonomous Underwater Vehicles (AUVs): their past, present and future contributions to the advancement of marine geoscience. Mar Geol 352:451–468
Xia QC, Li H, Song N, Wu ZL, Wang X, Sun X et al (2023) Research on flexible collapsible fluid-driven bionic robotic fish. Ocean Eng 276(8):1–10
Xie FR, Li Z, Ding Y, Zhong Y, Du RX (2020) An experimental study on the fish body flapping patterns by using a biomimetic robot fish. IEEE Robot Automat Lett 5(1):64–71
Xie FR, Zuo QY, Chen QL, Fang HT, He K, Du RX et al (2021) Designs of the biomimetic robotic fishes performing Body and/or Caudal Fin (BCF) swimming locomotion: a review. J Intell Robot Syst 102(1):13
Xie O, Zhu QX, Shen L, Ren K (2018) Kinematic study on a self-propelled bionic underwater robot with undulation and jet propulsion modes. Robotica 36(11):1613–1626
Yan CY, Zhang XQ, Ji ZY, Wang XL, Zhou F (2021) 3D-Printed electromagnetic actuator for bionic swimming robot. J Mater Eng Perform 30(9):6579–6587
Yan Q, Han Z, Zhang SW, Yang J (2008) Parametric research of experiments on a carangiform robotic fish. J Bionic Eng 5(2):95–101
Yang H, Ma J (2010) Nonlinear control for autonomous underwater glider motion based on inverse system method. J Shanghai Jiaotong Univ (Science) 15(6):713–718
Yang J, Feng JF, Qi D, Li YL (2016) Longitudinal motion control of underwater vehicle based on fast smooth second order sliding mode. Optik 127(20):9118–9130
Yang YC, Ye XF, Guo SX (2007) A new type of jellyfish-like microrobot. 2007 IEEE International Conference on Integration Technology, Shenzhen, China, 20-24 March 2007, pp 673–678
Yang YH, Chu CZ, Jin H, Hu QQ, Xu M, Dong EB (2023) Design, modeling, and control of an aurelia-inspired robot based on SMA artificial muscles. Biomimetics (Basel) 8(2):261
Yeom SW, Oh IK (2008) Fabrication and evaluation of biomimetic jellyfish robot using IPMC. Symposium on Mining Smartness from Nature held at the 3rd International Conference on Smart Materials, Structures and Systems, Acireale, Italy, 8-13 June 2008, pp 171–176
You SS, Lim TW, Jeong SK (2010) General path-following manoeuvres for an underwater vehicle using robust control synthesis. Proc Inst Mech Engine Part I: J Syst Control Eng 224(8):960–969
Yu JZ, Wang C, Xie GM (2016) Coordination of multiple robotic fish with applications to underwater robot competition. IEEE Trans Industr Electr 63(2):1280–1288
Yu JZ, Wen L, Ren ZY (2017) A survey on fabrication, control, and hydrodynamic function of biomimetic robotic fish. Sci China Technol Sci 60(9):1365–1380
Yu JZ, Wu ZX, Wang M, Tan M (2016) CPG network optimization for a biomimetic robotic fish via PSO. IEEE Trans Neural Netw Learn Syst 27(9):1962–1968
Yue CF, Guo SX, Li MX, Li YX, Hirata H, Ishihara H (2015) Mechatronic system and experiments of a spherical underwater robot: SUR-II. J Intell Robot Syst 80(2):325–340
Zhang SX, Yan WS, Xie GM (2017) Consensus-based leader-following formation control for a group of semi-biomimetic robotic fishes. Int J Adv Robot Syst 14(4):12
Zhang Z, Yang T, Zhang T, Zhou F, Cen N, Li T et al (2021) Global vision-based formation control of soft robotic fish swarm. Soft Robot 8(3):310–318
Zhao W, Yu J, Fang Y, Wang L (2006) Development of multi-mode biomimetic robotic fish based on central pattern generator. 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, Beijing, China, 9-13 October 2006, pp 3891–3896
Zheng XW, Wang W, Xiong ML, Xie GM (2020) Online state estimation of a fin-actuated underwater robot using artificial lateral line system. IEEE Trans Robot 36(2):472–487
Zhong Y, Song JL, Yu HY, Du RX (2018) Toward a transform method from lighthill fish swimming model to biomimetic robot fish. IEEE Robot Automat Lett 3(3):2632–2639
Zhou C, Cao ZQ, Wang S, Tan M (2008) Study on the pitching and depth control of biomimetic robot fish: study on the pitching and depth control of biomimetic robot fish. Acta Automatica Sinica 34(9):1215–1218
Zhou J, Huang C, Liu B, Wang TT (2014) A control system design of underwater robot for detecting underwater structures. Appl Mech Mater 536–537:1105–1109
Zhou L, Dong EB, Hang H, Kong XW, Yang J (2017) Design and research of a novel caudal-fin propulsion mechanism with two degrees of freedom. IEEE International Conference on Real-time Computing and Robotics (RCAR), Okinawa, Japan, 14-18 July 2017, pp 454–458
Zhou ZY, Jiang YQ, Li Y, Jian C, Sun YY (2018) A single acoustic beacon-based positioning method for underwater mobile recovery of an AUV. Int J Adv Robot Syst 15(5):1729881418801739
Zhou ZY, Liu JC, Pan J, Yu JZ (2023) Proactivity of fish and leadership of self-propelled robotic fish during interaction. Bioinspir Biomim 18(3):1748
Zhu KB (2018) Tracking and positioning technology of chemical plumes by underwater robots based on source distribution model. Chem Engine Trans (CET Journal) 71(1):451–456

Publisher's Note