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REVIEW ARTICLE

A Review: From Aquatic Lives Locomotion to Bio-inspired Robot Mechanical Designations

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Abstract

With the development of camera technology, high-speed cameras have greatly contributed to capturing the movement and posture of animals, which has dramatically promoted experimental biology research. At the same time, with the concept of bionics gradually gaining popularity among researchers, the design of robots is absorbing more and more biological features, where the interest in the bio-inspired robot is hewed out. Compared with the traditional robot, the bio-inspired robot imitates the motion pattern to achieve similar propulsion features, which may be more effective and reasonable. In this paper, the motion patterns of aquatic animals are divided into four categories according to their propulsion mechanisms: drag-based, lift-based, jet-based, and interface-based. And bio-inspired robots imitating aquatic prototypes are introduced and reviewed. Finally, the prospect of aquatic bio-inspired robots is discussed.

Keywords Bionic · Bio-inspired robot · Aquatic animal · Propelling mechanism · Structure design

1 Introduction

The ocean occupies more than 70% of the total area of the earth. It has become a widely recognized hypothesis that the ocean is the origin of life on the earth [1]. Since the 1960s, an increasing number of researchers have come to realize that the complexity of ocean exploration is beyond human capacity, and have gradually turned to the study of underwater robots. However, the unique seabed terrain and the constantly changing ocean currents have made the marine environment extremely complex, greatly increasing the design difficulty of underwater robots, leading to problems such as underactuation, over-redundancy, and power limitations. This has also resulted in a significant gap in the motion performance of conventionally designed underwater robots compared to land-based robots of the same size. To address the design challenges of underwater robots, the biomimetic approach has continuously directed research towards aquatic organisms. After a long process of evolution, aquatic animals have developed unique structures and motion patterns that differ from those of terrestrial organisms. This spontaneous mimicking behavior connects natural science and engineering, and has given birth to numerous classic works.

However, biomimetics is not simply about imitation. Some studies have provided new ideas for structural design from the perspective of biological anatomy, focusing on biological data such as muscle distribution [2], neuronal regulation [3], skeletal structure and hybrid cells [4], which have also inspired new driving modes. Compared to traditional robots that may move by controlling their joints, biologically inspired results bring a new logic for muscle-driven joints. From the perspective of the individual organism, understanding the essence of structural design is more focused on the stimulation that triggers external changes, such as propulsion parameter settings, changes in flow field structure [5], and biomechanical mechanisms [6]. Studying structural design from a population perspective focuses on the preservation of certain characteristics during evolution [7, 8] and the

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scalability of structural design brought about by schooling behavior [9]. From an engineering perspective, some studies focus on the specific benefits of biomimetic traits in design, such as improved motion performance, expanded application scenarios, and changes in control difficulties [10].

Therefore, bio-inspired robots, as a new direction derived from the intersection of biomimetics and robotics, are currently a hot research topic [11, 12]. Compared to traditional robot technology, bio-inspired robots have a completely different design approach. Traditional robots are function-oriented, task-driven, and built with modular components, which can be seen as the assembly and integration of structures. This type of robot technology is relatively mature, and they are mostly cable-controlled robots, unmanned submarines, unmanned boats, and so on. However, they have disadvantages in terms of motion performance, autonomy, and biological compatibility. Bio-inspired robots aim to mimic the characteristics of living organisms to improve robot performance. With different degrees of imitation and different features, bio-inspired robots have advantages that traditional robots do not have. This advantage is not only limited to improving robot performance itself but also has potential benefits for robot-biology interaction behavior due to its good biological compatibility [13].

Because of the different design concepts and the fact that biology and robotics have always been hot research fields, the concept of bio-inspired is considered a bridge between the two interests.

Furthermore, few reviews have been on aquatic bio-inspired robots in recent years. Kwak pays attention to the arthropods' locomotion and their applications in robotics [13], but he fails to pay attention to other aquatic animals. Sun gives descriptions of robotic fishes in details [13]. However, he summarized bio-inspired propulsion from the perspective of local characteristics, from the vibration of hydrofoil and the relationship between the body and fins, and did not discuss and analyze it from the perspective of the animal prototype. Similarly, Zhu focus on the underlying physics and the creation of mechanical systems utilizing the squid locomotion [13], where his focus is closer to the physical phenomenon caused by imitating this structure to promote rather than simply replicating the design itself. As for our work, we aim to introduce more comprehensively the research of aquatic animal prototypes and conclude the current works of bio-inspired robots, which also becomes the intention of our work.

To better explain our definition of bio-inspired robots, we drew Fig. 1, in which the yellow triangle is the three critical factors to be considered in robot design, and the green triangle is the three essential factors in biology prototypes. For robots, the size, control system, and mechanical system design are three crucial factors to be considered. From the biological point of view, evolution, motion pattern, and species schooling are the focus of biology.

Based on the proposed concept of bio-inspired robots, this article's main contributions are as follows. Firstly, this article classifies the motion modes of animals to introduce and summarize the current research on the motion mechanisms of aquatic animals. Secondly, according to the size of bio-inspired robots, this article provides separate introductions to the structural design of conventional and small-scale robots. Finally, this article discusses the motion performance and development direction of bio-inspired robots to summarize the research content of this review.

And the paper is expanded as is. Section 2 introduces the aquatic locomotion mechanisms of animals considered to be the bionic prototype. Section 3 presents the mechanical structure design of small bio-inspired robots, while the mechanical structure design of common-size bio-inspired robots is introduced in Sect. 4. Finally, Sect. 5 discusses several existing problems and future developments for bio-inspired robots.

2 Locomotion Mechanism of Aquatic Prototype

After a long-time evolution, lives in the water have evolved their unique motion skills. The classification we adopted in this paper is based on Daniel, and Steven's work, where they have classified the relationship between the aquatic life and the water into four types, including drag-based swimming,

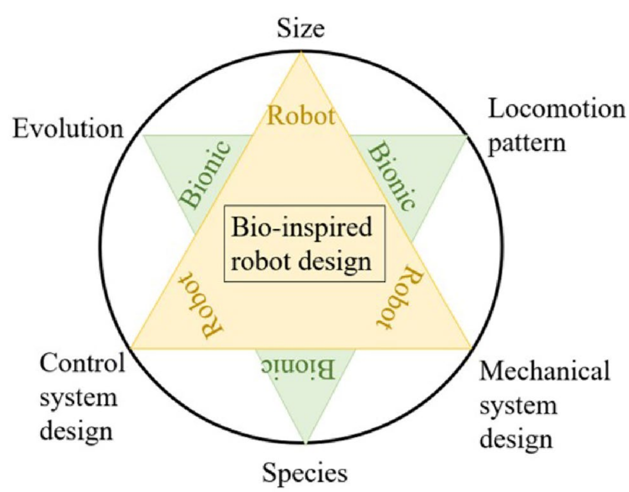


Fig. 1 Main factors that will affect the performance of the bio-inspired robot

lift-based swimming, direct-reaction swimming, and interfacial swimming [142, 162].

2.1 Drag-based Swimming

The drag-based swimming includes flagellar swimming, ciliary swimming, or setal paddles swimming in low Renold numbers and a single bilateral pair of appendages paddling or serially arranged bilaterally paired appendages paddling in moderate and high Renold numbers [16, 17]. The ciliary and flagellum are two different structures, although both structures have similarities. The swimming of ciliated organisms can be reckoned as the collaborative swing of many cilia, which can maintain a special fluid environment over the ciliated surface. The swing process can be reckoned as a beat, which can be separated into two distinct phases: the effective stroke and the recovery stroke, according to Blake's work [18].

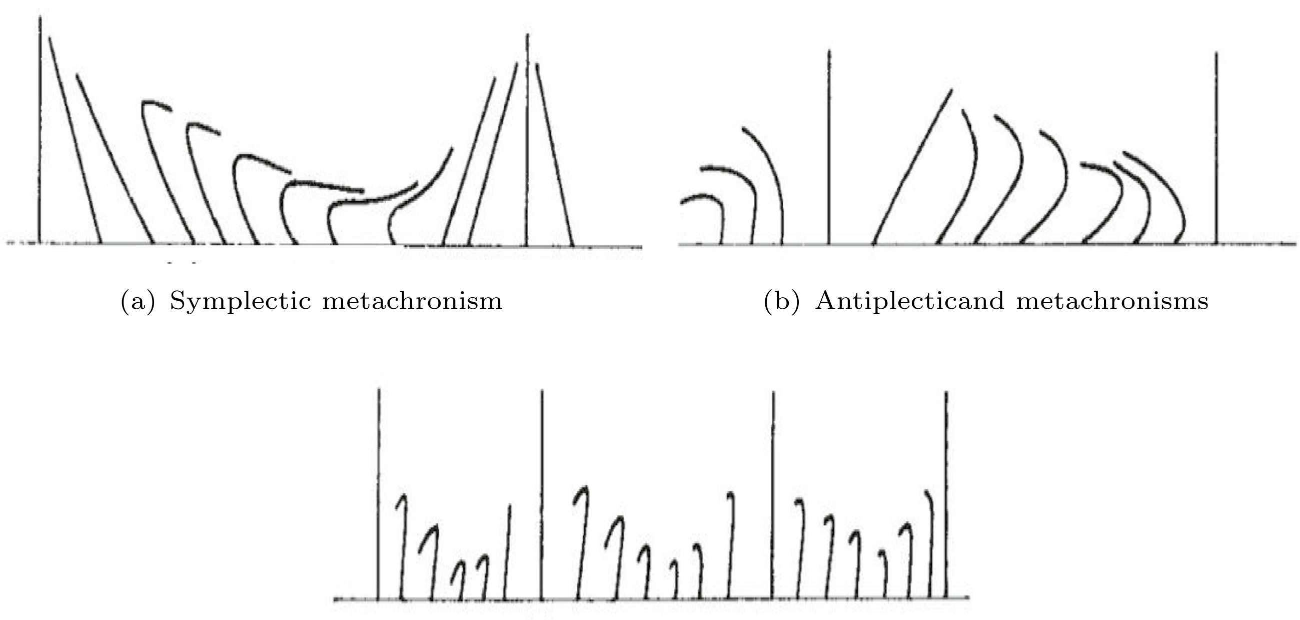
The illustration of various types of cilia stroke is shown in Fig. 2. It can be observed in all three types that during the effective stroke, the cilia seem to be separated into several small sections like the stave list. And the single cilia curves get close to their neighbors. The general depiction is that the anterior to the beating one has just completed its stroke, while the posterior is just beginning its effective beat. Thus, the central cilium, which is also the beating one, is bisecting the angle made by the other two [18]. And the most widely studied ciliated animals also include paramecium [19] and ctenophores [20, 21].

Flagellum structure is very similar to cilia swimming [22–29], but the main difference is that the cilia are swinging while the flagellar is rotating during swimming. The evidence of flagellar rotating was first discovered in 1973 by Berg, that a bacteria swam forward by rotating flagella, rather than swimming like tadpoles that people had always thought before [30].

Moreover, the rotation of flagella is evoked by the motor, according to Macnab's work. The flagellum is connected by a motor embedded in the inner cell wall. When the flagellum rotates counterclockwise, it will drive the flagellum's rotation and bind it into the flagellum bundle. The bundle propels and generates the propulsion force of forward movement. When the flagellum motor rotates counterclockwise, the flagellum bundle spreads, and the direction of the propulsion force from a single flagellum is different (Fig. 2, 3). Thus the bacteria complete the tumbling movement [31].

Based on this feature, the swimming process of a flagellated bacterium can be summarized as moving forward intermittently and tumbling to keep approaching the destination. The tumbling behavior achieves when the flagellum bundle is pushed apart, and abrupt reversal in the case of polarly flagellated cells [33]. Furthermore, many researchers focus on the near-shear effect of the flagellated cells to better promote the movement of small pipeline robots [34–36].

Drag-based swimming also includes appendages paddling, such as asynchronous motion. An example is krill.

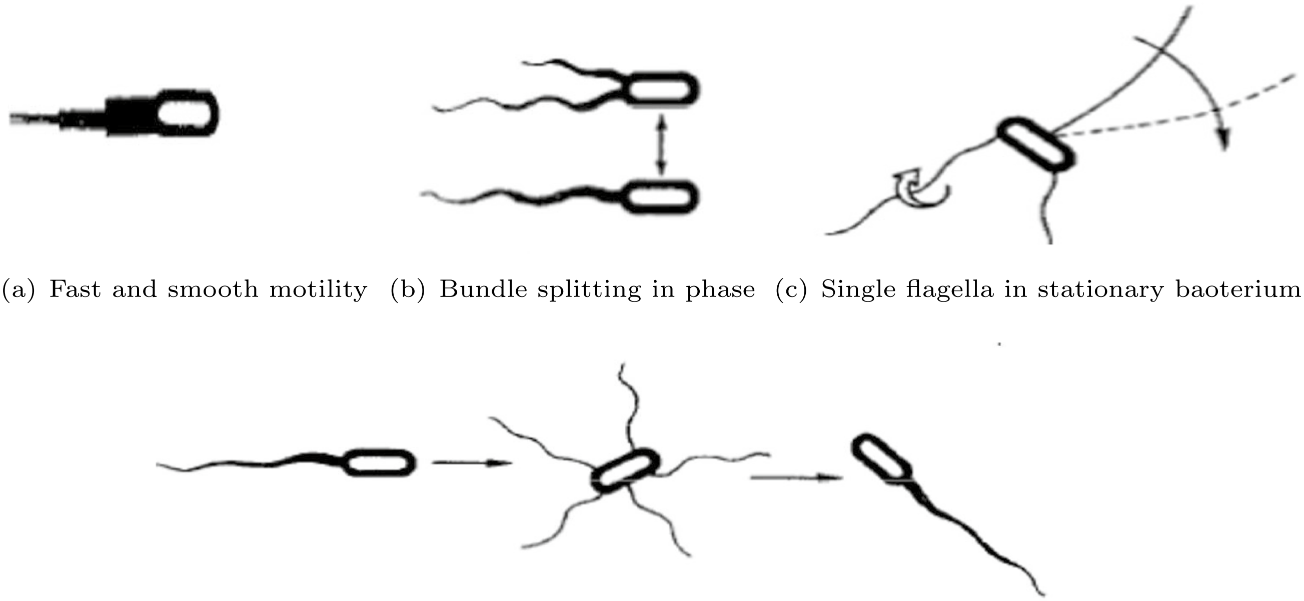


(a) Symplectic metachronism

(b) Antiplecticand metachronisms

(c) Diaplectic metachronal

Fig. 2 Illustrations of metachronal cilia wave patterns[18]



(a) Fast and smooth motility (b) Bundle splitting in phase (c) Single flagella in stationary baoterium

(d) Complete process of flagellar bundle re-formation and recovery

Fig. 3 Line drawings of brtoterial flagella visualized by high intensity dark field mioroscopy [31]

Krill have five pairs of pleopods [20]. And other kinds of shrimps have similar swimming behaviors and mechanisms (Fig. 4).

When the krill swims, the five pleopods complete rhythmic movement, which will react to the water flow, and the protopodite drives the endopodite to paddle through the joints. The swinging order of the pleopod is from the back to the front [37]. According to Hu's work, when the first pleopod finished swinging, the fifth pleopod started to swing, and each gastropod bends at different angles. Different pleopods showed different bending shapes at the same time. The paddling swimming usually occurs at low speed, with an average speed of 0.3–25 cm/s [38, 39]. In an emergency, krills are more inclined to use the tail movement to obtain short-term acceleration to escape. The tail section is unlocked at this time, and the forward reversal accelerates the backward movement. When the tail section overlaps, it will stretch again, with a swing frequency of about 3–4Hz. The tail movement is unstable, with an average speed of 27 cm/s and a maximum speed of 45 cm/s [32].

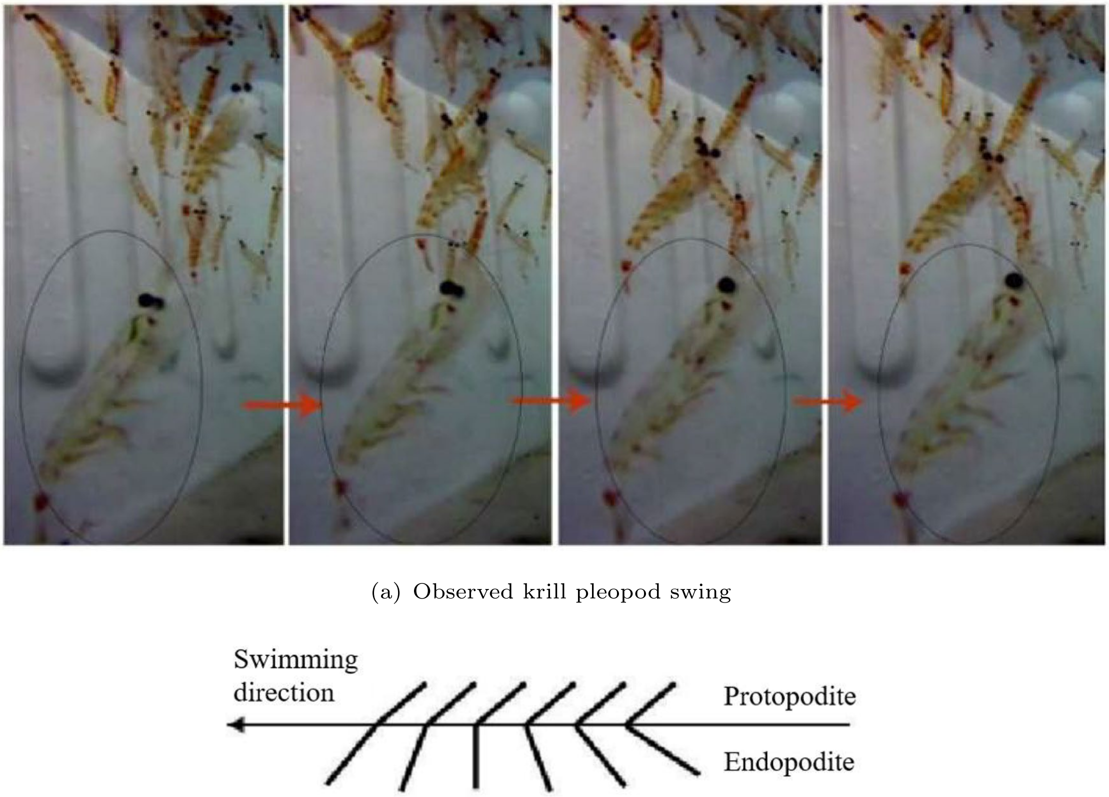
Similarly, mantis shrimp and krill belong to the same Malacostraca class and have similar paddling movements. At first, many reasearchers foucus on the strike dynamics of the mantis shrimp [40–42]. Later, it was found that the rowing movement was ubiquitous at various sizes by diverse organisms [43].

Mantis shrimp swim via metachronal rowing, where the pleopods stroke sequentially, from the last pair to the first pair (Fig. 5). Kuvvat and David present a time-resolved planar present time-resolved using two-dimensional Particle Image Velocimetry(PIV) measurements of a swimming peacock mantis shrimp (Odontodactylus scyllarus). And the mean swimming speed after measurement is 0.2–1.9m/s. Furthermore, the stroke is not purely metachronal, with a prolonged phase lag between initiation of the first and the fifth pleopod power strokes [44]. In the same way, many studies are focusing on the lobster movement. However, this kind of stroke on lobster is not apparent because its gastropods are relatively hard. Many studies believe it is a mixture of walking and swimming rather than swimming [45–47].

Drag-based swimming also include some kinds of fishes, where almost all fishes areregarded as drag propulsion or lift propulsion. The classification based on the driving position is widely adopted in that the fish propulsion can be divided into Body and/or Caudal Fin propulsion (BCF) mode and Media and/or Paired Fin propulsion (MPF) mode [48]. Generally speaking, MPF mode fishes are regarded as lift propulsion. Some works show that anguilliform, subcarangiform, and carangiform are propelled with the add-mass method instead of the lift-based method. However, the research on vortices evoked by the lift-based method is still substantial under the add-mass method [48]. Thus, in this paper, we will introduce all fish in the lift propulsion section.

2.2 Lift-based Swimming

The lift-based swimming is rooted in paired lateral propulsors, such as wings or fins, and a single caudal propulsor,



(a) Observed krill pleopod swing

(b) Different forms of a pair of pleopod at different times

Fig. 4 The rythmic movements of krill gastropods [32]

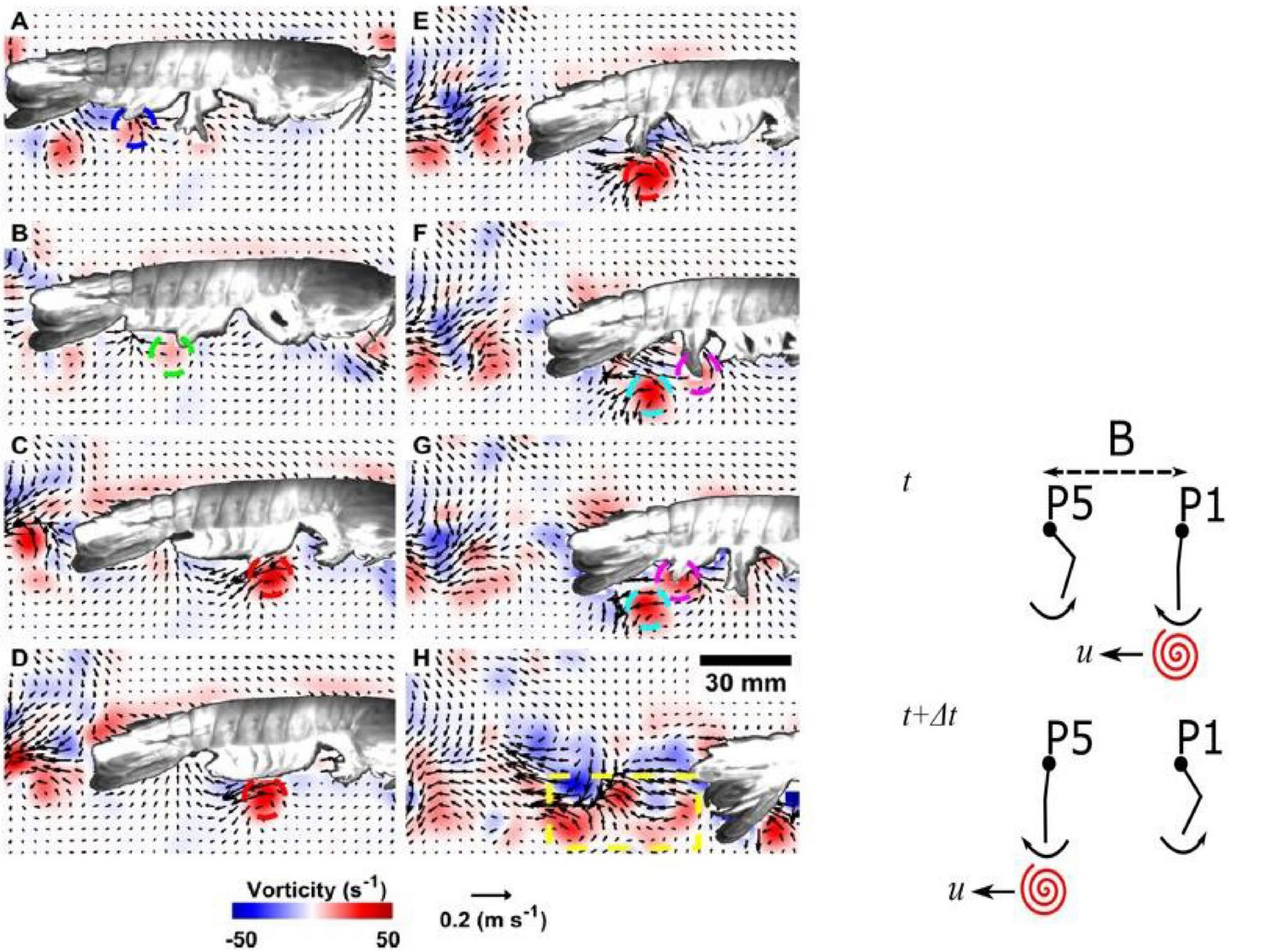
such as tails or flukes. And the main prototypes of lift-based swimming are fish species. According to others' works, almost 15% of the fish families use non-BCF modes as their routine propulsive means. In BCF mode, the propulsive wave traverses the fish's body in an opposite swimming direction at a faster speed than the fish moving speed. And Fig. 6a reflects changes in the propulsive wave's wavelength and amplitude envelope and it also shows how the thrust is generated.

Anguilliform swimmers elongate with little or no narrowing at the caudal peduncle, which makes them slender and lack separation between the body and tail, especially in eels. Thus, we commonly assume that the anguilliform swimming will involve the whole body propelling in large amplitude (Fig. 7). However, other anguilliform swimmers, such as sharks and needlefish have a slight narrowing at the caudal peduncle and are more separated on the fins [49]. They undulate from one-third to almost all of their bodies, which depends on their swimming speed and is shared with one or more complete waves present at a time [50].

A numerical simulation on anguilliform swimming hydrodynamics is constructed by Borazjani [51]. Eric uses two PIV cameras to observe the effect of the swimming speed and the wake structure [52, 53]. Gills have reviewed the anguilliform swimming characteristics in detail [54]. Similar movements are also observed in the subcarangiform mode. The undulation amplitude is limited in the front and increases only in the back of the body [48]. Gambella has reviewed the subcarangiform mode swimming in detail [55], and Stephen uses the juvenile (7–8 cm) and adult (27–30 cm) stages of the antarctic teleost Notothenia neglecta Nybelin to discuss the kinematics characteristics [56].

It is more pronounced that the undulations are further confined to the last third of the body length, and thrust is provided by a relatively stiff caudal fin in the case of carangiform swimming [48]. Iman employs numerical simulation to investigate the hydrodynamics of carangiform locomotion as the relative magnitude of viscous and inertial forces [57]. Kambe focused on the dynamics phenomenon of the passive body response incented by the active tail oscillations. More precisely, it is to understand the contribution of tangential frictional resistance, the virtual-mass response, and the reaction forces to the nonactive oscillations [58].

Thunniform mode is the most efficient mode evolved after years in aquatic environment, which can maintain high cruising speeds for long periods [48]. Thus, many bio-inspired robots have been inspired by thunniform locomotion in recent years, where some focus on the dynamics



(a) Flow fields record

(b) Interpleopod vortex phase matching mechanism

Fig. 5 The swimming mechanism of mantis shrimp [44]

characteristics using numerical methods [59–61] and others employ the power production, and energy saving mechanism [62, 63].

Moreover, ostraciiform locomotion is a purely oscillatory BCF mode. The relatively stiff caudal fin oscillates like a pendulum and the body remains stiff. Fish utilizing ostraciiform mode are usually encased in rigid bodies and forage their complex habitat using MPF propulsion [64].

Rajiform swimming is always linked to bird flights, which use pectoral fins flapping and is mainly found in rays, skates, and mantas. Thrust generation of this MPF mode involves the vertical undulations passing waves along the flexible triangle-shaped pectoral fins[65]. And their kinematics and hydrodynamics are investigated to understand the propulsion mechanism [25, 65, 66], using numerical method [35].

Similarly, the force is generated by passing undulations down broad pectoral fins in diodontiform mode. Up to two full wavelengths may be visible across the fins, while undulations are often combined with flapping fins [48]. While in many cases of amiiform swimming mode, the fish uses long-based dorsal fin to swim, and the body axis is held straight[67]. Gymnotiform mode can be considered the upside-down equivalent swimming mode of the amiiform mode because the propelling position is a long-based anal fin, and the biofield dynamics during their swimming performance are discussed [68–71]. Moreover, both the anal and dorsal fins undulate to propel in balistiform locomotion, as introduced in the work mentioned [72].

To sum up, the total characteristic of the BCF mode is high speeds and great thrust and acceleration performance but low maneuverability at a low speed. And the main characteristic of the MPF mode is slow mean speeds, high propulsive efficiency, excellent maneuverability, and turbulence resistance. With the different behaviors of different species

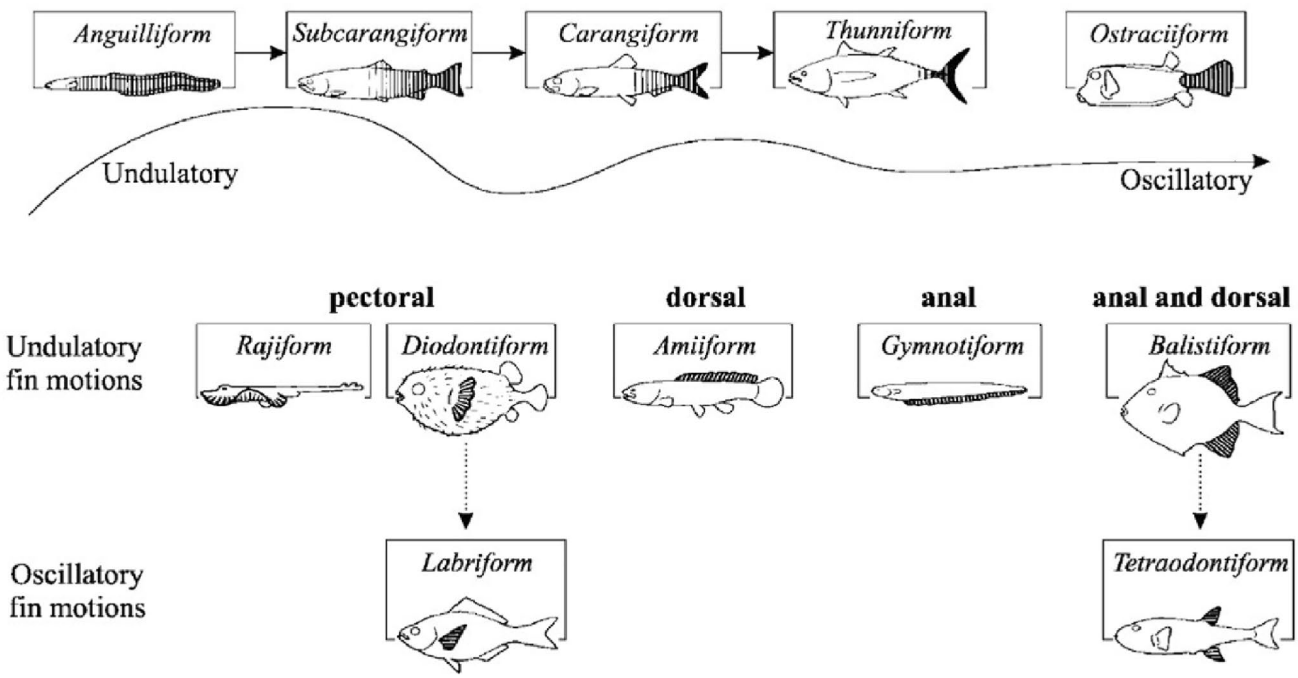


Fig. 6 The classification of the fish propulsion mode, including BCF mode and MPF mode [48]

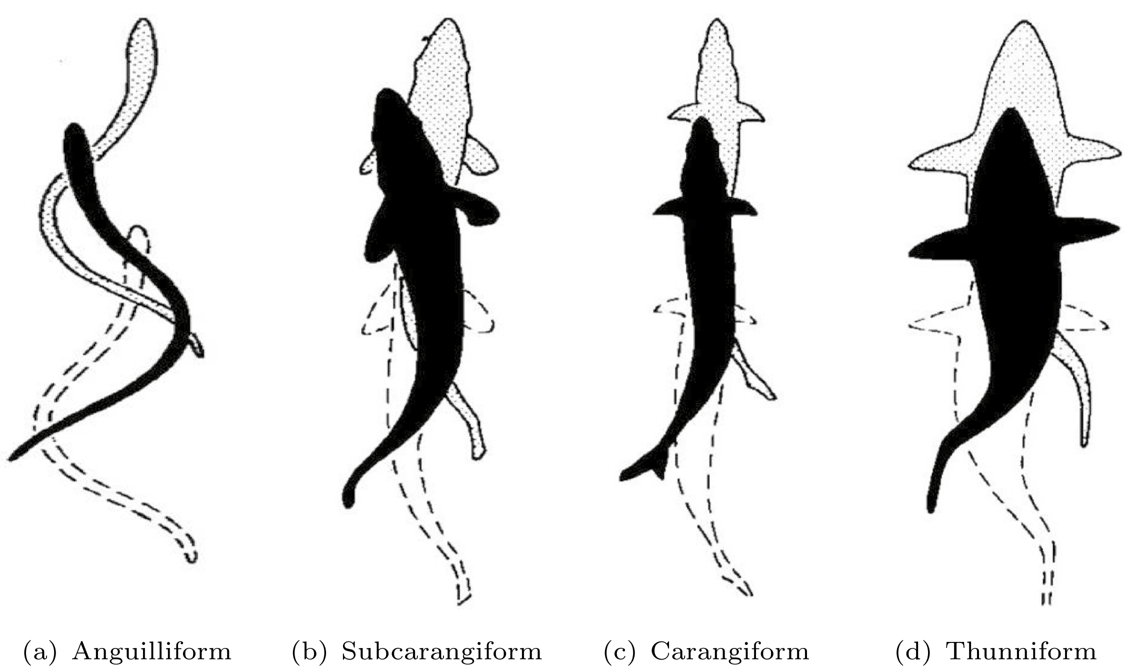


Fig. 7 Gradation of BCF swimming movements [48]

of fish in their living environment to avoid natural enemies and predators, different species adopt different swimming patterns that are closely related to their self-protection and survival behavior, as discussed in this paper.

2.3 Jet-based Swimming

The direct-reaction swimming uses pulsating jets or paired jets. The animal will fill the muscle cavity and eject water to make it move in the opposite direction to the ejected water. During the movement period, the pumping and drainage process will bring about fluctuations in mass and resistance as shown in Fig. 8. The jet-based swimming behavior is often seen in cephalopods such as squid, jellyfish, starfish, scallops, and so on.

Qualitatively, squid jets were periodic, steady, and prolonged emissions of fluid that exhibited an elongated core of high-speed flow [73–75]. Similarly, jellyfish have a unidirectional water chamber that produces a continuous jet propulsion cycle phase followed by a stationary phase. Many researchers focus on the inner swimming mechanism of its muscles contraction and extension [76–78], and some others focus on the vortex and energy capture [79, 80], while others focus on the Reynold number [81] and hydrodynamics [82].

The scallops escape by a simple structure with one large adductor muscle, two valves, a muscular mantle, and the elastic hinge ligament which exerts jet flow [83]. In view of the mass change caused by water spraying and water absorption, the added-mass effect is obvious. And two other mechanisms the flow-induced pseudo-elasticity and pseudo-viscosity are also obvious according to Cheng's work [84]. This simple structure and fast startup performance are full of attraction that many works are about the mechanism and performance analysis of the propulsion [85–87].

Nevertheless, compared with the tail oars used by the fish, jet swimming is an energy-consuming way. With the

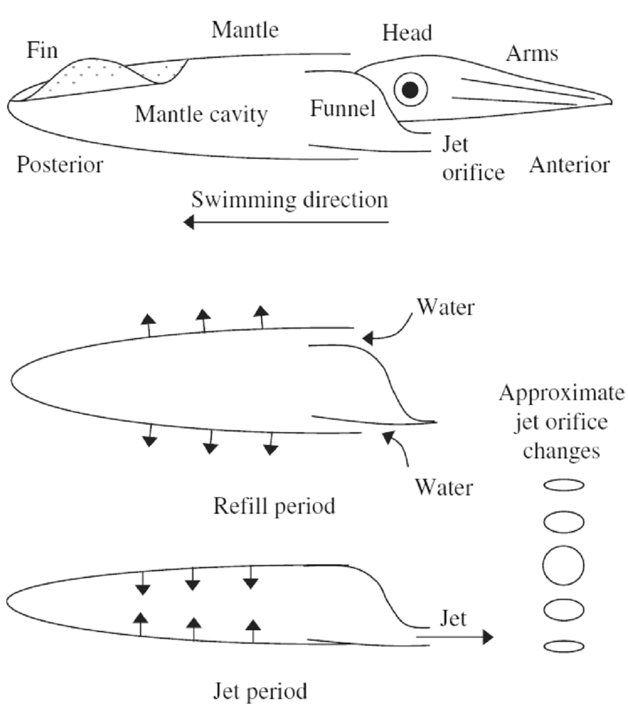


Fig. 8 Sketch of the structures and propulsive mechanisms of the long-finned squid [73]

increase in animal size, the relative efficiency of jet propulsion further decreases. However, the stop-start motion is meaningful in providing high-speed bursts, especially when capturing prey or avoiding predators, which makes cephalopods the fastest marine invertebrates.

2.4 Interface-based Swimming

The interface-based swimming is actually "interface-based propulsion", for it utilizes surface tension to support and propel. Large water-walkers, such as the basilisk lizard [88, 89], rely on a combination of form drag, added mass, and gravitational forces generated by vigorous slapping of the free surface for both weight support and propulsion. Small water-walking insects rely on surface tension to support. And water strider generates propulsive forces from form drag and curvature forces. Others may propel by capillary forces, or Marangoni stresses [90].

Apart from small cases, some animals can achieve short-range running over water, such as small Anolis lizards and green iguanas [89]. However, only basilisk lizard can walk on the water surface from infancy to adulthood, with an average speed of 1.4 m/s.

In minor cases, animals live on the water surface and stay afloat by surface tension, which is 72.8 mN/m under 20 °C [92]. The interface-based insects include coral treaders (Hermatobates weddi, Hermatobatidae), sea skaters (Halovelia septentrionalis, Veliidae), and water striders (Metrocoris histrio, Gerridae) [91]. Moreover, the infraorder Gerromorpha has two basic gaints one is alternating double tripod gait and the other is the synchronous stroke gait [93]. Water striders' well-known high speed and maneuverability is mainly rooted from the synchronous stroke gait according to Andersen's work. And Fig. 9 shows the classification of locomotion and species.

Compared with common-scaled animals, insects must climb a meniscus due to surface tension when they come ashore. Although we can see with the naked eye that the water surface, such as ponds and pools is flat, there is a terrain on the water surface because of the surface tension under the perspectives of insects. When insects try to move to land or floating objects of the water surface, they must climb a meniscus topology. The menisus may form because the obstacles are soaked. In their view, the meniscus is like a frictionless mountain range [94]. So it brings additional branches for learning how to climb a meniscus for tiny animals [95, 96].

Some other insects can release a small volume of surfactant from their legs, which will result in the difference in surface tension gradient and use the Marangoni effect to propel it forward, such as small velia and Velia, rove beetles [97] and so on. To be mentioned, for nonwetting arthropods,

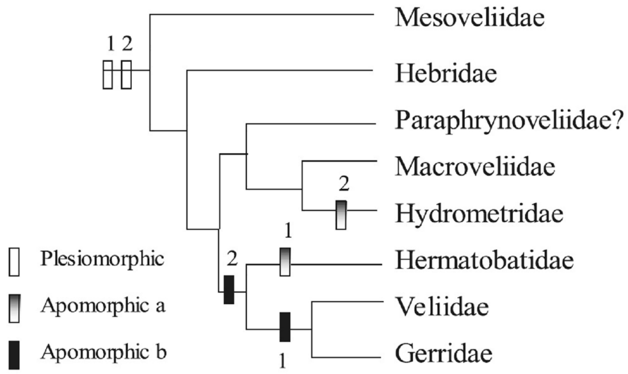


Fig. 9 Phylogeny of Gerromorpha, according to Andersen and Weir's work [91]

some organisms release surfactants on their water-contacting limbs, which can transfer chemical energy to kinetic energy.

2.5 Summary

Based on the previous analysis, we classified and summarized the propulsion mechanism of aquatic animals, as shown in Table 1. Muscles generate force and different distributions of the muscles will lead to different force generation and momentum generation, presenting different mobility characteristics that are competitive in the living environment.

Specifically, we need to note that the lift propulsion in the table actually duplicates some resistance propulsion fish. We have mentioned them in both lift propulsion and drag propulsion because many fish are not fully lift propelled or drag propelled, and some fish may experience a state of joint influence of lift propulsion and drag propulsion as they grow and develop and alternate motion modes. The process of resistance propulsion may still bring about changes in the vortex structure, which is important in the study of lift propulsion. Since this chapter summarizes the mechanisms of biological movement, we believe that this repetition is reasonable.

Table 1 Propulsion and classification of aquatic lives

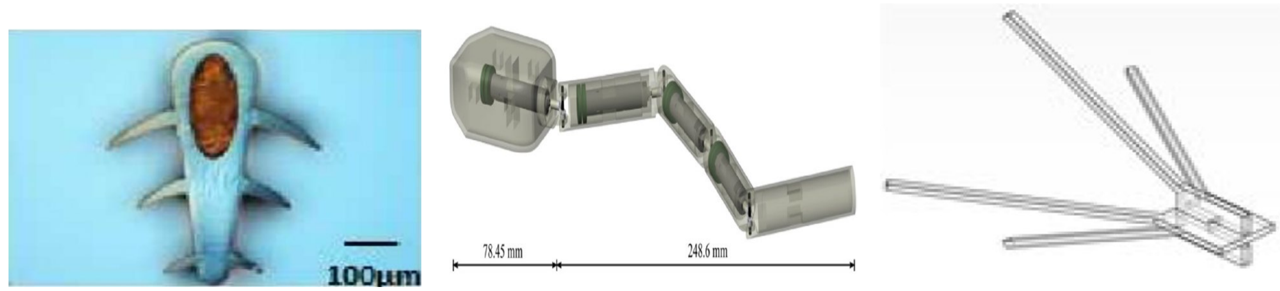
	Small size		Common size	
Category	Advantages	Disadvantages	Advantages	Disadvantages
Drag-based[1]	Good turning performance High effieciency	Bad swimming performance	High speed when tail swimming High manuverability High flexibility	Low speed when gastropod swimming, Unstable speed when tail swimming
Lift-based[2]			High propulsive efficiency, Great turbulence resistance, Great thrust acceleration	Low maneuverability at a low speed Slow speed
Jet-based[3]			Good escape performance High maneuverability	Low locomotion efficiency, Low Froude efficiency, Unstable speed
Interface-based[4]	High speed Good turning performance Good speed stability	Special chemical substances Meniscus topology obstacle	High skating speed High efficiency	Poor static performance

[1]Drag-based prototype include: ciliary (paramecium [19], ctenophores [20, 21]), flagellar (*Escherichia coli* [26–29]), shrimp (Palinuridae, euphausiacea [38, 39], odontidactylidae [42]), BCF (anguilliform, subcarangiform, carangiform)

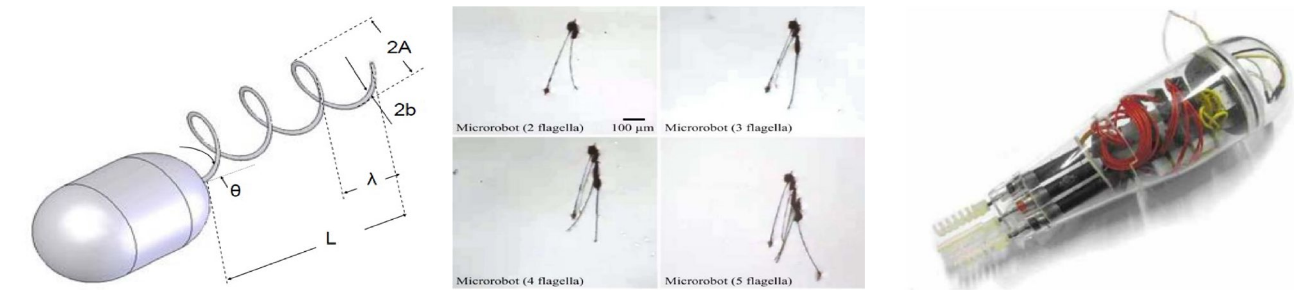
[2]Lift-based prototype include: BCF (anguilliform, subcarangiform, carangiform), BCF (thunniform, ostrathatrm [48]), MPF(rajiform, diodontiform, amiiform, gymnotiform, balistiform [48])

[3]Jet-based prototype include: cephalopods (squid [73], jellyfish [77]), pectinidae (scallops [84, 86])

[4]Interface-based prototype include: basilisk lizard [88, 89], gerromorpha (hermatobatidae, veliidae, gerromorpha [93])



(a) small magnetic driven ciliate robot [98] (b) Flexible single flagella inspired robot [99] (c) Magnetic driven multiple flagella inspired robot [100]



(d) Fixed angle flagella inspired robot [101] (e) Soft multiple flagella inspired robot [102] (f) Small multiple flagella inspired swimming robot [103]

Fig. 10 Drag-based inspired robot. The prototype of the above robots are ciliates and flagellates

3 Mechanical Structure Design for Small Bio-inspired Aquatic Robot

In Sect. 2, we have discussed the propulsion mechanisms of aquatic lives. And according to the consensus of bionic-inspired designation, there are many works focus on the prototype discussed before. And in this section, the mechanical structure will be cited and to compare with the real-lives motion performance.

Due to the influence of various physical effects on the scale reduction of the robot, the surface product force becomes the dominant force compared with the body force. Compared with the conventional-size robot, the microrobot needs a unique motion design, such as electrostatic force and surface tension, as the driving force.

The small robot we mentioned in this paper refers to the robot whose length is generally less than 20 cm. Because size is a relatively vague concept, the standard to depict the size of a robot needs to be clarified. The microrobot is generally a millimeter-level robot, or its weight is no more than 0.1g. The normal-sized and conventional-sized robot is 40 cm or more. Moreover, the concept of "large" is usually mentioned with bio-inspired aquatic vehicles, which may be consistent with the size of a submarine. Emphasized is that the large bio-inspired robot is contrary to the original intention of our works, in which we mainly focus on the common-sized and small-sized prototypes and robots. And thus, we collectively refer to small and micro as small and the other size as usual in this paper. Furthermore, in this chapter, we mentioned only the small robot.

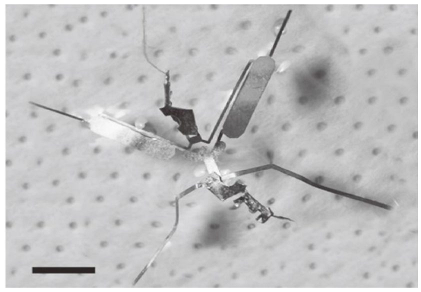
3.1 Drag-based Design

The structure can be illustrated from the small organisms to construct artificial flagellated or ciliated small-propellers (Fig. 10).

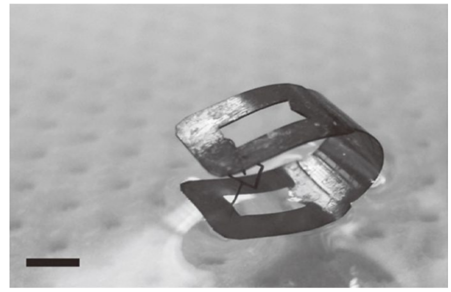
Zheng proposed a small magnetic-drive robot with side meniscus multi-cilia, whose length, width, and thickness are 450 μm, 320 μm, and 40 μm, respectively. Its head consists of a nickel plate. The small robot is driven by the magnetic field and swings up and down to provide forward thrust for the robot [98]. Moreover, many robots will choose the magnetic drive because it is challenging to achieve conventional drive means in this size [14].

Khalil investigates a sperm-cell propulsion system [104]. This system consists of a sperm cell with a 42 μm magnetic head and a 280 μm flexible tail. Zhu set up a flagellum robot with three-helix propellers with a length of 129 mm and a diameter of 43 mm [103]. Beckham creates an E.Coli tail-inspired structure with a metallic spring with 260 μm wire

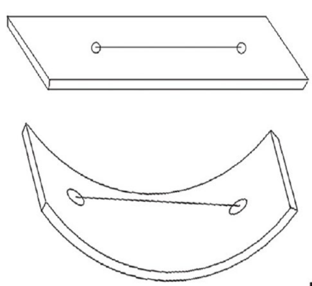
(a) Schematic diagrams of Robostrider 1 (R1)[109]



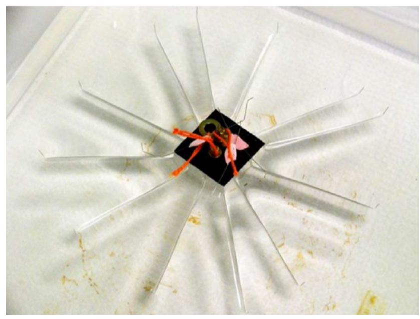
(b) Schematic diagrams of Robostrider 2 (R2)[109]



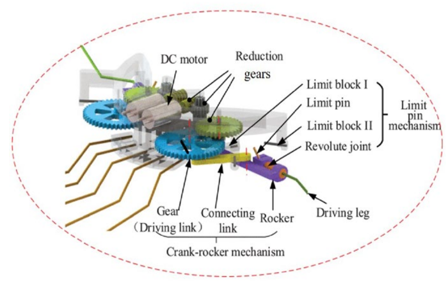
(c) Schematic diagrams of Roboleaping (RL)[109]



(d) Schematic diagrams of Roboclimbing (RC)[109]



(e) Twelve teflon legs robot [110]



(f) Miniature water-walking robot [111]

Fig. 11 Interface-based inspired robot, where **b**, **c**, are micro-sized and **a**, **d**, **e** and **f** are small-sized robot. The prototype of the above robots is water striders and other aquatic insects

diameter and 6.6mm helical diameter[101]. Also, a small robot for neurosurgical intervention in the ventricular system is propelled using flagellum propelling according to Kosa's work [105], which is a very promising branch in the application of small robots. Moreover, the flagellum small-robot for medical application can be abstracted from the works [106]. Small robots for medical purposes can also perform point-to-point drug delivery, and micro-interventional surgery operation, and disease monitoring. And Hossein introduced a swimming microrobot with flagella motion that can follow the desired three-dimensional trajectory [107].

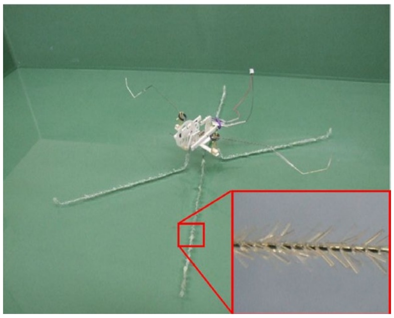
Notably, the small robot in an accurate scale of cells is different from what we think of as a robot but can be considered a robot broadly. Magdanz presents a single-step electrostatic self-assembly technique to fabricate IRONSperms. And the soft magnetic small swimmers emulate the sperm cells motion mode [108].

3.2 Interface-based Design

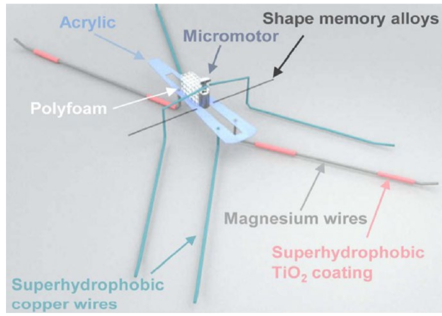
The structure csuperhydrophobicity of insects to construct small-propellers. David focused on water striders and developed a series of small robots called Robostrider [109], which have many series.

Robostrider R1 weighs 0.35 g, while the Robostrider R2 only weighs 0.07 g. Robostrider R2 is closer in size and weight to its natural counterpart. However, the speed of the R2 is slower than R1 as well as the counterpart. And a small robot Roboleaper (RL), imitating the leaping motion of Podura Aquatica, was constructed that is ten times larger than its natural counterpart, where it weighs 0.04 g and can move 50–100 cm/s. And the counterpart moves only 50 cm/s. It consists of a curved leaf spring with a latch engaged by hand and released by heating with a soldering iron. Thus, it can achieve jumping on the surface. The design of the small mechanical meniscus climber (RC) is inspired by the water leaf beetle larva Pyrrhalta. It can arch its back to generate a menisci shape at its head and tail to wet and propels itself up the meniscus. The speed of the designed small robot RC is 1 cm/s, while the speed of the counterpart is 10 cm/s (Figs. 11, 12).

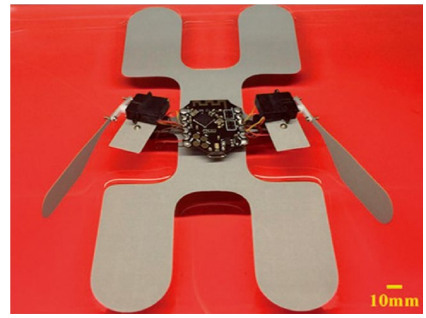
Song designed a small robot inspired by the unique scaling advantage of long-legged insects. He attempts to use Hydrophobic Teflon to optimize the surface tension of the long and thin legs. The prototype has twelve 7-cm-long Teflon-coated legs and can carry 8.3 g payload [110, 118]. Yan focused on the deformation reaction of the insects' slender legs on the water surface [111]. The small robot is 4.9 g



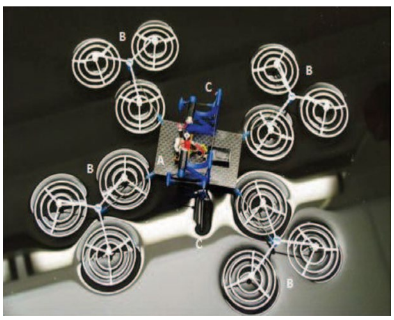
(a) Hexapod water strider robot [112]



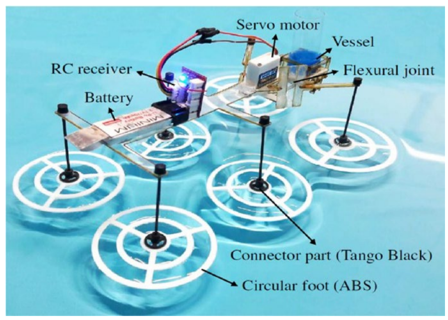
(b) Self-propelled robot [113]



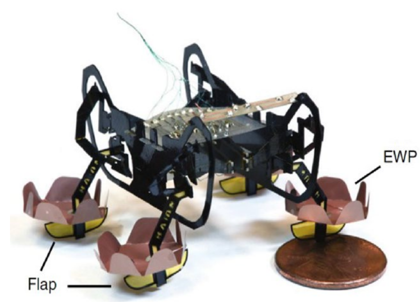
(c) Robot strider with excellent super hydrophobicity leg [114]



(d) The diagram of STRIDER II [115]



(e) Malagoni propelling robot [116]



(f) Malagoni propelling boats [117]

Fig. 12 Interface-based inspired robot, where **a**–**d** use new materials to design the legs and **d** can extract electricity from the water surface to achieve self-proplled and **e** and **f** using Malagoni effect to propell

and has a total length of 160 mm. Ozcan proposed a small robot called STRIDER II, which uses 12 new circular footpads. Each footpad is 4.2 cm in diameter, the small robot is 21.75g, and the maximum forward speed is 7.15 cm/s [115]. Sun fabricated a 27.9 g robot with excellent super-hydrophobicity legs to support the moving motion [114]. The supporting legs can load no more than 42.5 g with a maximum depth of 5.05 mm over the water. Wang designed a small robot that can achieve self-powering with artificial legs. The special structure makes it possible to extract electrical energy from the water surface with an output voltage of 1.38 V and an output current of 25 mA. A motor and Shape Memory Alloy (SMA) is coupled and the small robot can paddle through its superhydrophobic side legs. And the average forward speed can reach about 1.45 cm/s [113].

On the other hand, the propelling boats can use a separate reservoir to release the solution spontaneously, which is similar to the release of the surfactant during the malagoni propelling [116, 117, 116, 117].

3.3 Summary

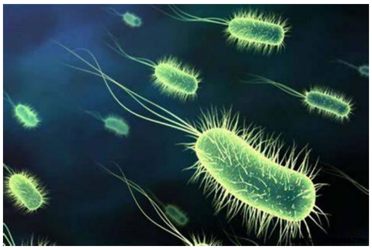
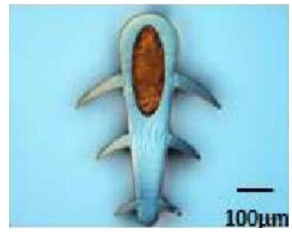
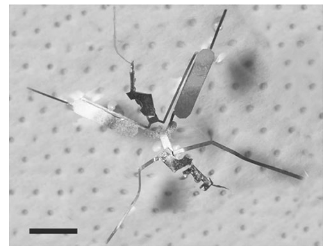
Due to the scaling factors, the structural design and driving methods of small aquatic robots are significantly different from those of conventional sized robots. In particular, in the case of small scale and low Reynolds number, the robot completely immersed in the liquid environment is dominated by viscous force, so the process of its implementation and driving is complex. Traditional propeller propulsion is also difficult to function at this scale. This also directly led to the use of special materials in many works to further enhance inertial forces and complete driving. There are also some tasks that maintain the aquatic environment of aquatic robots, but their application scenarios do not involve liquid immersion, that is, by imitating insects, they can stand on the water surface, so they can be driven by surface tension.

We provide a small aquatic robot inspired prototype and inspired robots as shown in Table 2.

4 Mechanical Structure Design for Normal-sized Bio-inspired Aquatic Robot

The small-size robot inspired by the aquatic animal discussed in this paper is well addressed in the previous section. And the common-sized robot will be exemplified in this

Table 2 Prototype and small bio-inspired aquatic robot

Characteristic	Prototype	Robot
Drag-based		
Interface-based		

Note: The drag-based robot is inspired by *E. coli* [98], the interface-based robot is inspired by waterstrider [109]

chapter. There are many bio-inspired aquatic robots designed for conventional size, where some have been mentioned in the previous reviews [15, 123]. In this chapter, we will introduce the common-sized bio-inspired robot in an organized way.

4.1 Drag-based Design

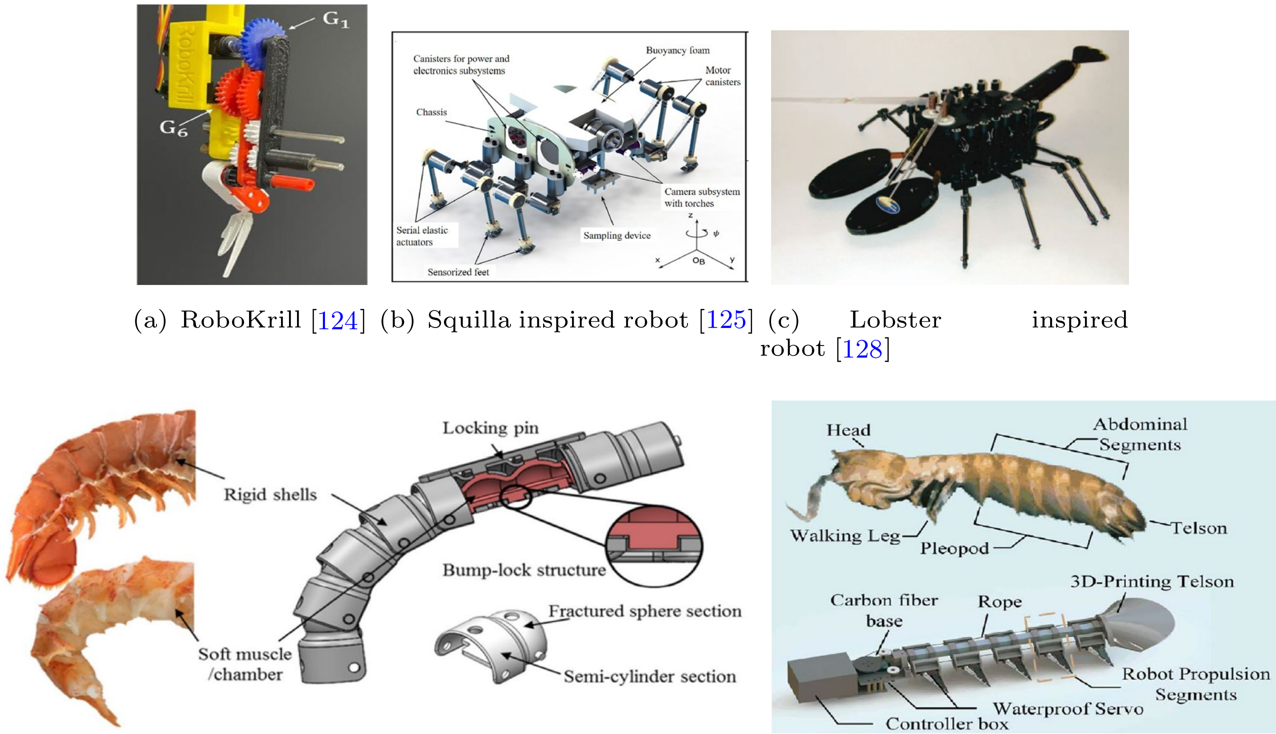
Since many drag-based prototypes are microbial structures, we focus more on shrimp and fishes, especially in BCF mode in this paper.

Sara designed a drag-based swimmer RoboKrill, which is inspired by ten-times-magnified krills [37, 124]. In order to balance the design, the beat frequency of Robokrill is set as 0.57 Hz, while the live krill presents a 5.7 Hz record in nature. Kinematic analysis of the designed structure shows it can successfully reproduce the kinematics of the prototypeproduces when it produce fast-forward swimming. Li introduced a Squilla-like soft robot based on new materials, including dielectric elastic materials (DE), Polyethylene Terephthalate (PET) and PLA (3D printing material). The external size of the robot is 9 cm×5 cm×7 cm. The squilla-like robot is abstract as an abdomen and two feet, where the abdomen is mainly consist of muscle attached to the skeleton. DE is used to design the abdominal joint muscle, and PET is used to set up the abdominal joint skeleton, and PLA is used to fill the whole body [125]. Moreover, the maximum speed of the designed robot is 2.66 cm/s. Chen developed a hybrid actuator inspired from the lobsters. It can generate reconfigurable tail bending utilizing the internal soft chamber. When the soft muscle contracts or relaxes, the the external rigid shell follows this movement because of the connection of the traction piece [126]. Dian designed a six-wheeled modified shrimp robot that can move along the pipelines and pass obstacles within 65 mm [127]. Anyer designed a biomimetic lobster. The overall size of the robot is 8 in.×5 in.. The legs consist of three degrees of freedom. And the eight legs are stabilized by anterior and posterior hydrodynamic control surfaces [128, 129]. Chen used shrimp as a prototype and designed a robot using 3D printing, with a size of 600 mm×65 mm×75 mm. Its structure features sturdy flexible swimming feet for swimming propulsion, as well as a rope driven spine for bending the body and can reach a maximum swimming velocity of 0.28 m/s, about 0.46 Body Length per second (BL/s) and a minimum turning radius of 0.36 m [130] (Figs. 13, 14 and 15).

4.2 Lift-based Design

As concluded before, the lift-based design is mainly inspired by fish.

The MPF-inspired robot can be addressed mainly by the manta. Cai designed bionic robotic fish propelled by paired pectoral fins oscillating in a structure with a two-stage slide-rocker fin and one servo motor. The swimming velocity is 0.26 m/s (0.55 BL/s) [131]. Furthermore, he promotes the bionic fish's maximum linear forward swimming speed to 0.7 BL/s [13]. Wang designed a disc-like robotic fish inspired by freshwater stingrays. The maximum velocity of the designed robot is 4.3 cm/s (0.18BL/s) [140]. Cai designed a coordinate control method for Underwater Biomimetic Vehicle-Manipulator System (UBVMS) [148] with



(a) RoboKrill [124] (b) Squilla inspired robot [125] (c) Lobster inspired robot [128]

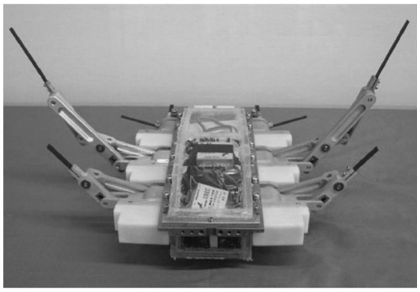
(d) Hybrid lobster inspired robot [126] (e) Shrimp inspired robot [130]

Fig. 13 Drag-based inspired common sized robot, where **a**, **c** are common sized, **b**, **d** and **e** are small sized robot

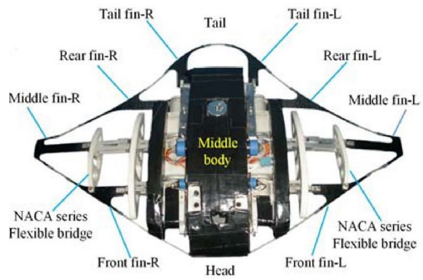
fins and he promoted his design to grasp marine products on the seabed. And the swimming ability of the Hybrid-Driven Underwater Vehicle-Manipulator System (HD-UVMS) is promoted by using thrusters via two unique long fin propulsors [149]. His design incorporates the characteristics of fish propulsion, adopting a long fin scheme, with superior propulsion steering performance, high control accuracy, and enormous potential for biomimetic applications. Bai proposed a novel flippers-driven UVMS, which is equipped with six biomimetic flipper propulsors to produce thrust [150]. His work provided a complete control plan and conducted real experiments, which has great value.

The BCF-inspired mode has many species involved. Song designed robotic fish inspired from crucian crap. The robitic fish is driven by double cam [133]. The best swimming performance will achieve when the tail frequency is in the range of 0.1–1.0Hz. When the caudal peduncle thickness is 1 mm, the maximum swimming speed will reach about 0.3 BL/s. Wang designed a novel electromagnetic-driven joint for bionic fish and is able to achieve high-frequency swing during the swimming process. The robot is composed of three special joints [134, 151]. The fastest swimming speed is 0.18 m/s. Muralidharan demonstrated a subcarangiform-inspired robotic fish driven by materials of SMA. The propelling mechanism is based on spring and it can achieve a forward speed of 24.5 mm/s [135]. Szymark and his team have designed a Cyberfish based on BCF mode fishes, which has four degrees of freedom. The designed robotic body consists of four rigid sections connected with rotary kinematic pairs, sealed with rubber rings and plain bearings. And each of the rigid parts is driven by servomotor and gears [136, 152].

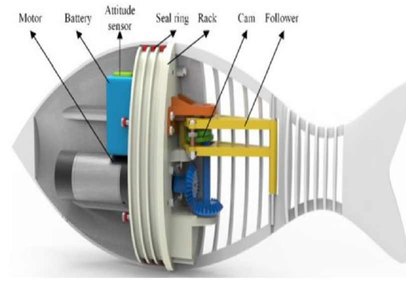
Jiao designed a BCF mode robot fish using soft material based on a limit-type antagonistic dielectric elastomer actuato (DEA) and can achieve a maximum speed of 22.7 mm/s [137]. Ren developed a robotic fish according to the morphology of Carangiform fish, with an overall size of approximately 60 cm. The electrical construction of the robotic fish consists of four servo motors, a small processor, a wireless communication module, two aluminum links, a lunate plastic tail, two plastic pectoral fins, sensors, and peripherals [138]. Nguyen presented a fish robot with a non-uniform flexible tail (NFT), and the maximum speed is about 0.7 BL/s [139]. Chen designed a biomimetic fish like robot based on tuna, with a total length of 709 mm, a spine length of 270 mm, and a tail fin length and width of 160 mm and 80 mm, respectively [141]. Yu designed an integrative model that takes account of both kinematics and dynamics o explore the possibility of leaping with an untethered swimming robot [153]. Chen designed a soft robotic fish using soft actuator and



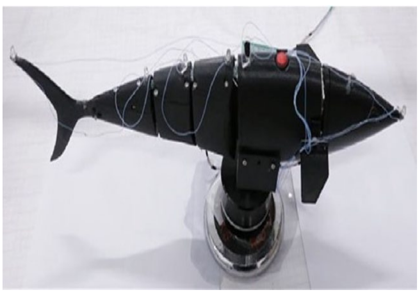
(a) Cownose ray inspired robot [131]



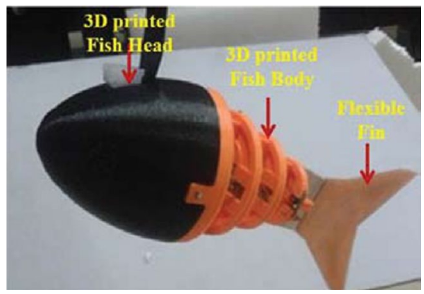
(b) Improved cownose ray inspired robot [132]



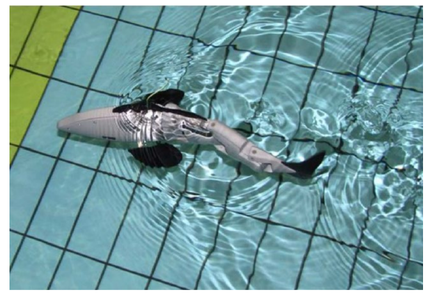
(c) Crucian carp inspired robot [133]



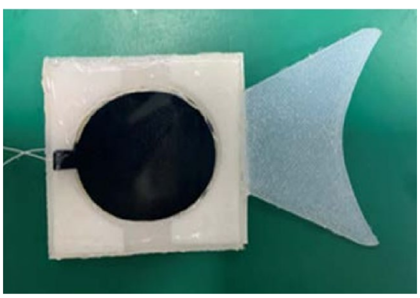
(d) Fish-driven joint inspired robot [134]



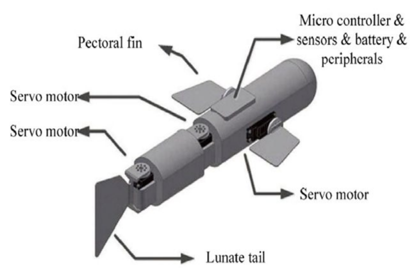
(e) Subcarangiform robotic fish [135]



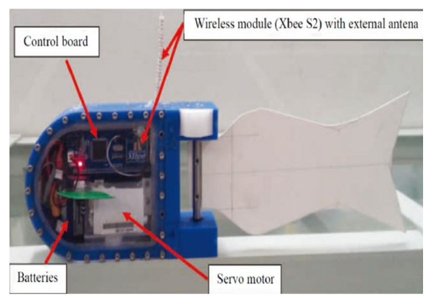
(f) The physical map of CyberFish [136]



(g) DEA robotic fish with passive tail [137]

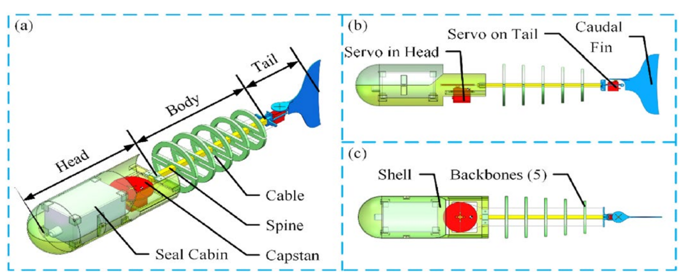


(h) Carangiform robotic fish [138]



(i) NFT inspired robotic fish [139]

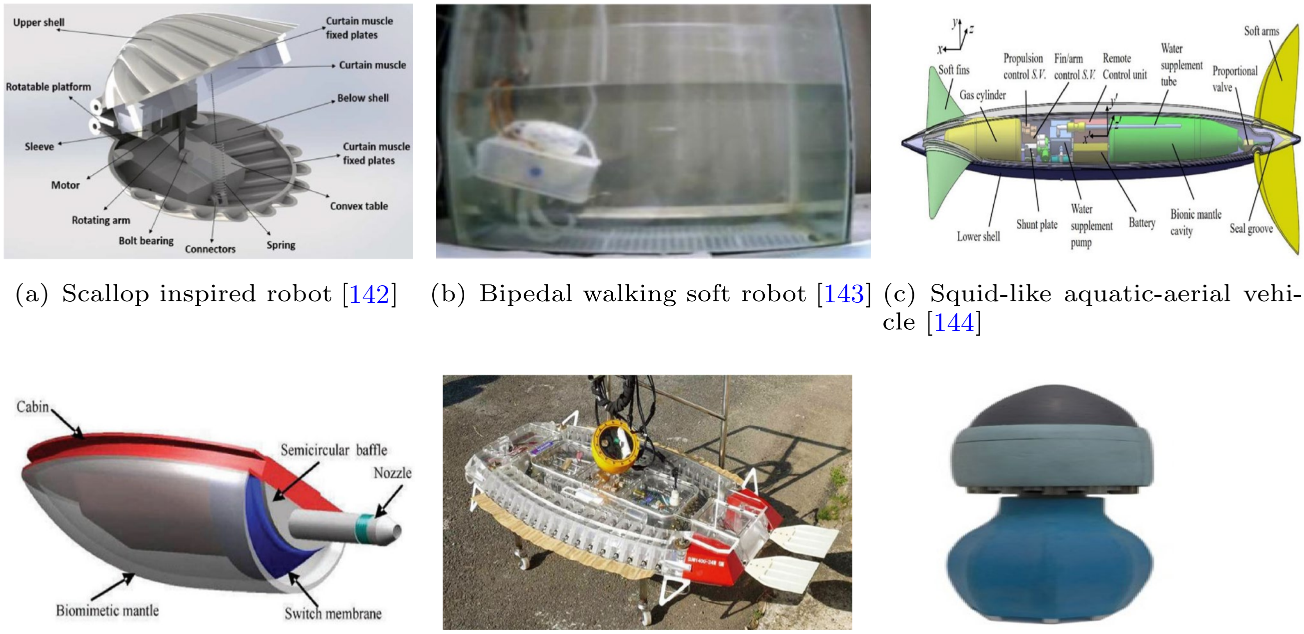
(j) Freshwater stringray inspired robot [140]



(k) Freshwater stringray inspired robot [141]

Fig. 14 Lift-based inspired robot, where **a**, **b** and **j** are inspired from MPF fishes and **c**, **d**, **e**, **f**, **g**, **h**, **i** and **k** are inspired from BCF fishes

achieved acuate motion control, where the neural network-based motion model was constructed through neural network training with data collected by visual sensor [154]. Lv achieved disturbance rejection control using a Disturbance Observer-based Control (DOBC) framework on a UBVMS, with four flippers [155] and furthermore, he achieved the



(a) Scallop inspired robot [142] (b) Bipedal walking soft robot [143] (c) Squid-like aquatic-aerial vehicle [144]

(d) Cuttlefish inspired robot [145] (e) Squid-like large robot [146] (f) Jet propulsion inspired robot [147]

Fig. 15 Jet-based inspired robot, where **a**, **c**, **d**, **e** and **f** use jet to propel and **b** simulate the walking with octopus feet. Specifically, the **c** is a small robot and **e** is a large robot and others are common sized

collision-free planning and control on the designed UVBMS [156]. The platform he designed is relatively perfect in terms of structural optimization, and its further control work and visual work have significantly improved the autonomy of the platform he built.

4.3 Jet-based Design

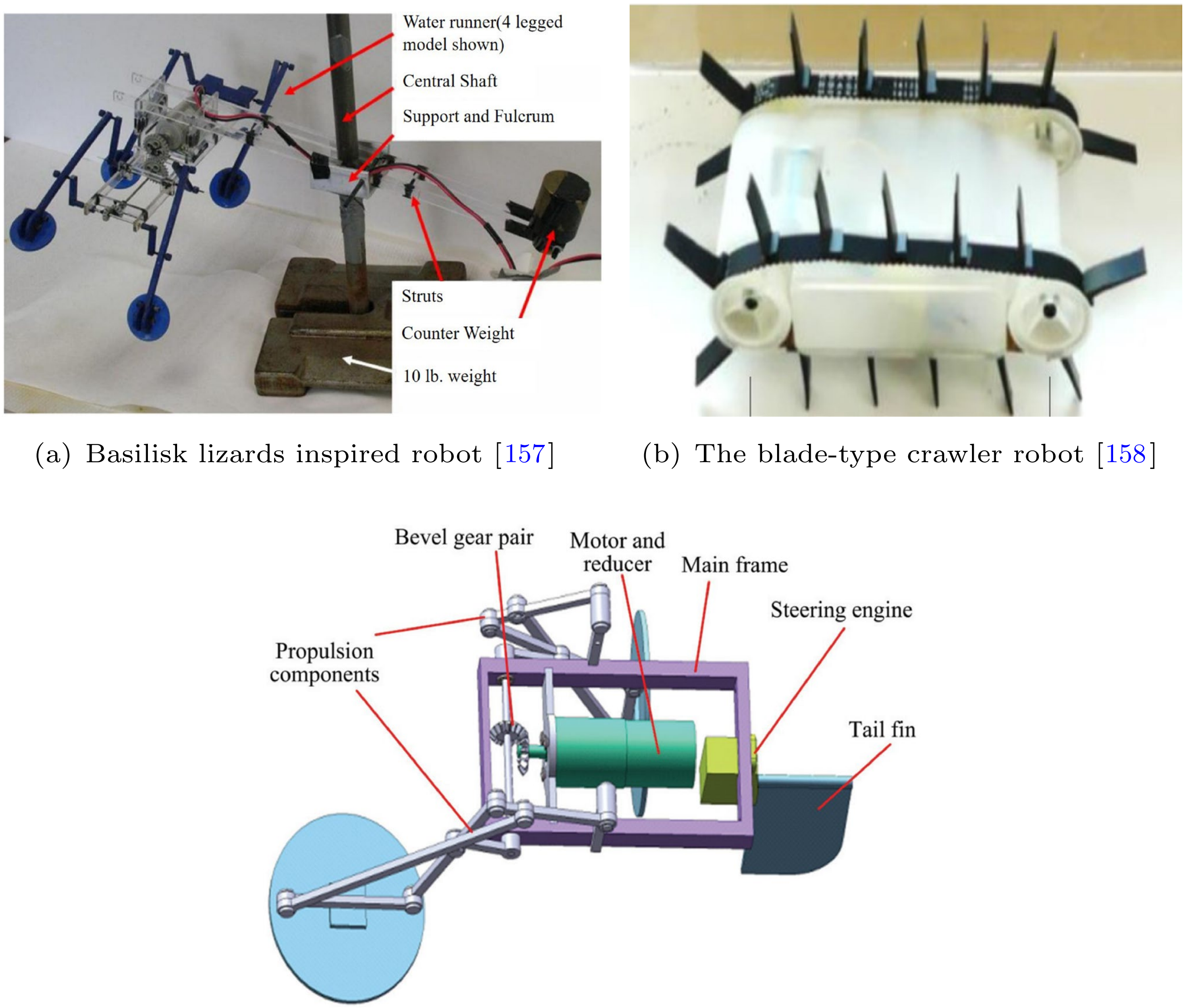
The jet propulsion structure's core is a cavity, which can perform suction and injection actions to swim (Fig. 16).

Wang designed a jet-based propulsion robot inspired by scallops. The scallop robot consists of two shells, a unique motor, and a curtain muscle. The motor aims at driving the periodical open and close of the shells and the muscle is designed to control the water absorbing and spraying during swimming [142, 145]. And the jet propulsion mode enables the robot to move up to 1.4 BL/s. Hou designed an aquatic-aerial vehicle inspired by soft morphing fins and arms abstracted from squids. The fins can spread and fold by expansion/contraction of the inflatable cavity structure under positive/negative pressure [144, 160]. Wu designed a bipedal walking robot inspired by the coconut octopus. It is based on a Spring-Loaded Inverted Pendulum (SLIP) model and use walking instead of swimming to move forward. And the average speed is 6.48 cm/s, while the maximum instantaneous speed is 8.14 cm/s [143]. Rahman developed an underwater robot inspired by squid, which has a length of 140 cm, a width of 714 cm, a thickness of 10 cm, and a total weight of 62.8 kg [146]. Gao developed a biomimetic mantle jet propeller. The SMA wires are set as the actuators and the soft silica gel was chosen as the body material. The thrust and frequency of the jet are variable, where the swimming speed can be adjusted as the jet thrust and jetting frequency increase. Moreover, the maximum speed is 8.76 cm/s (0.35 BL/s) [145]. Bujard focus on the resonance of the jet-propulsion efficiency and test through a squid-inspired robot [147].

4.4 Interface-based Design

Since insects mainly use the interface-based propulsion mode, the bionic prototype for robots of normal size is mainly basilisk lizards. And there are many teams that focus on this kind of special prototype and bio-inspired lizards.

Floyd proposed a design that can run on the surface of the water like basilisk lizards using a pair of identical four-bar mechanisms with a 180° phase shift. The two-legged models can experimentally provide 12–15 g/W of lift while four-legged models can provide 50 g/W of lift [157, 161–165]. Yamada developed a blade-type crawler robot with a simple and reliable mechanism capable of traversing uneven terrain at a high speed [158]. Xu designed a bio-inspired basilisk lizard based on Watt-I planar linkages, which has the average propulsion force of 1.3 N



(a) Basilisk lizards inspired robot [157]

(b) The blade-type crawler robot [158]

(c) Bio-inspired basilisk lizard based on Watt-I planar linkages [159]

Fig. 16 Interface-based inspired robot, where **a**–**c** are inspired by basilisk lizard

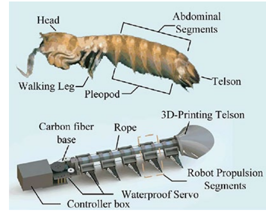
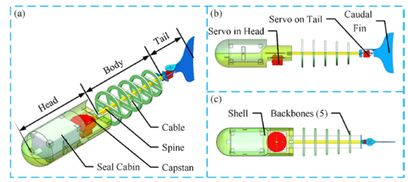
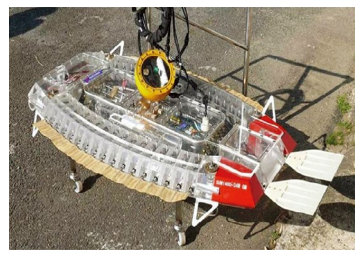
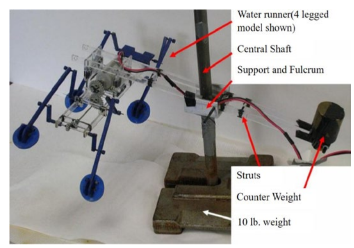
and a body tilt angle of 5° [159, 166]. The designs mentioned are able to achieve the running motion on the water surface.

4.5 Summary

Under conventional size, the design of aquatic robots is easier compared to smaller sizes. The prototype inspired by its biology is still dominated by fish. We think this may be because fish have more extensive application scenarios than scallops, shrimps or large water Voltigeur, and their mobility, speed and other comprehensive performances are excellent, so they have advantages in design and implementation. Meanwhile, due to the fact that the aquatic environment not only includes liquid environments, but also has land and sea conditions in real-world underwater applications, robots such as lobsters that can adapt to both modes of water and land in aquatic environments are also a research hotspot.

We provide a commen-sized aquatic robot inspired prototype and inspired robots as shown in Table 3.

Table 3 Prototype and normal-sized bio-inspired aquatic robot

Characteristic	Prototype	Robot
Drag-based		
Lift-based		
Jet-based		
Interface-based		

Note: The drag-based robot is inspired by shrimp [130], the lift-based robot is inspired by BCF mode fish [141], the jet-based robot is inspired by squid [146], the interface-based robot is inspired by basilisk lizards [157]

5 Discussion

In previous chapters, we have introduced many motion mechanisms of bionic prototypes and bio-inspired robots. Based on these previous works, we have discovered many interesting phenomena.

Firstly, compared to traditional design methods, bio-inspired approaches enable robots to achieve better motion performance and propulsion efficiency, and possess better scalability for expanding research on bio-inspired robot swarms, human-robot interaction, and bio-robot hybrid swarms [167]. However, the implementation of such designs is more challenging than traditional methods. This is because bio-inspired methods may utilize novel materials, such as certain alloys and soft materials, which may exhibit highly nonlinear behaviors and pose significant challenges in control modeling. Moreover, certain new materials possess magnetic or electric field responses, which shift the control strategy towards magnetic field control to drive the robot's motion. For certain special materials that rely on chemical reactions for self-propulsion, closed-loop control strategies are transformed into predicting the initial coating of the chemical layer. However, this design approach using new materials faces obstacles in large-scale production applications, and the size of robots produced using new materials is generally small.

Thus, currently, many bio-inspired robots tend to use traditional structures to mimic biological movements, enabling the robots to combine ease of production and traditional control methods while achieving better performance to complete the process of bio-inspiration. However, whether this degree of imitation can be considered as bio-inspired remains ambiguous, leading to our first question.

How can we scientifically and systematically evaluate the process of bio-inspiration? Does mimicking or reproducing certain animal movement patterns mean that we are engaged in bio-inspiration work? This is also a common problem in current bio-inspiration work, namely the lack of metrics to quantify bio-inspiration work.

To be sure, the current structure design restored the biological movement mode. At the same time, the research on many biological prototypes and corresponding bio-inspired robots is very detailed. The biological features are clear, and the bio-inspired robot has complete functions and high overall reducibility. It has the advantages that the robot designed by traditional methods does not have. It can better explore nature and complete its mission.

Currently, the evaluation of bio-inspiration work is still in its infancy, and some studies attempt to evaluate the bio-inspired robot's dynamic parameters using hydrodynamic parameters of animal movement mechanisms, such as Strouhal number and Froude efficiency, and compare these parameters with the hydrodynamic parameters of actual animal movement processes. Does more accurate feature extraction represent more advantageous bio-inspiration work? Or does higher overall robot performance reflect better bio-inspiration work?

Thus, we believe that future work should not only focus on animal movement mechanisms and patterns, but also on evaluation methods for the bio-inspiration process, to guide the development of bio-inspired robots.

Beyond the evaluation methods for the bio-inspiration process, we need to think more about the motivation for selecting bio-inspiration prototypes. Although this article mainly analyzes the robot's movement patterns and structural design, it does not cover the robot's perception, interaction, and control, which we believe are also essential factors to consider in robot design. From a bio-inspired perspective, the impact of biological movement patterns and mechanisms on robot structural design is the most intuitive. This mainly reflects in the appearance design, kinematic and dynamic models, and structural design of the mechanical structure. In nature, the appearance and movement of organisms are the first things that catch our attention. This also evokes our third question: How to choose animal prototypes for bio-inspired process? Is it reasonable to choose solely on the robot's application scenario? Or in aquatic environments, where there are many animals, how do we determine which ones the robot needs to mimic?

In particular, we have to mention that the locomotion employed by the prototype cannot necessarily be considered the optimal option for the prototype. The development of locomotion is actually the compromises for social activities, including feeding, predator avoidance, and energy conservation. At the same time, as a game between individuals and populations, it also affects the direction of evolution to a certain extent, which jointly determines the locomotion pattern.

According to biological theory, an animal's own movement pattern can be considered a good way of moving in a certain environment, even if it may not be optimal. Therefore, how to choose a bio-inspiration prototype? What features should be mimicked? To what extent should it be mimicked? This also connects with our first question: What extent of imitation is most beneficial for robot design? Is creating a bio-inspired robot that replicates the animal's movement pattern exactly considered excellent work?

Furthermore, we have noticed a lack of holistic awareness in the entire design process of bio-inspired robots. This may also be due to an excessive focus on individual features, which weakens another significant advantage of bio-inspired robots, namely their scalability.

As we have mentioned above, the locomotion characteristics are the needs of individual performance and social attributes, such as courtship, mating, foraging, and natural enemies. The performance and parameters displayed are not necessarily the best in kinematics but must be the best considering all factors. Therefore, bio-inspired robots should not only focus on imitating a single feature but also the interaction between them. An example is the attitude of biology prototypes and other creatures toward artificial features and schooling effects, where we can regard bio-inspired robots as a whole to study the relationship between biology and artificial products and among biologies.

Furthermore, this scalability can help expand the range of applications for robots. For example, the construction of mixed robot-real animal communities can integrate the range of real biological activities, expand the application scope of robots, and enhance the overall performance of underwater robot communities.

However, the progress of this work still requires the exploration of the establishment of bio-inspired standards. Based on the above analysis, we believe that the current work on bio-inspired robots does indeed show performance improvements from the perspective of individual robots, but it has not yet reached the upper limit of bio-inspired work. Even though bio-inspired robots show improved performance compared to traditional robots, they still have a long way to go in achieving the comprehensive qualities of biological prototypes.

In the future, research on bio-inspired robots should not be limited to improving specific performance through bio-inspired design. Instead, more attention should be given to macro-level research, such as the impact of structure on global design, scalability of robot groups, and establishment of bio-inspired standards, to scientifically guide the bio-inspired process and improve the overall performance of bio-inspired robots. Additionally, comprehensive imitation of biological features should be conducted, and the causes of animal locomotion patterns should be evaluated to extract different animal motion features for environmental applications.

Furthermore, attention should be paid to the practical difficulties encountered during the manufacturing process of bio-inspired robots, with a focus on reducing production costs and enabling the ability to cluster and be mass-produced. Specifically, for aquatic bio-inspired robots, it is necessary to expand their range of motion and medium to allow for cross-medium movement, with potential applications in water, underwater sand, and air. In summary, the development of bio-inspired robots remains a challenging and long-term task, with a need to address macro-level considerations, such as how structure impacts global design, the scalability of robot groups, and the establishment of bio-inspired standards, to guide the bio-inspired process and improve the overall performance of bio-inspired robots. Additionally, comprehensive imitation of biological features and evaluation of the causes of animal locomotion patterns should be conducted to extract different animal motion features for environmental applications.

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Data Availability The authors confirm that all the data supporting the findings of this study are available within the reference article and its supplementary materials.

Declarations

Conflict of Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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