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An overview of biomimetic robots with animal behaviors

Zihang Gao [a,b], Qing Shi [a,b,*], Toshio Fukuda [b,c], Chang Li [a,b], Qiang Huang [b,c]

[a] Intelligent Robotics Institute, School of Mechatronical Engineering, Beijing Institute of Technology, Beijing 100081, China
[b] Beijing Advanced Innovation Center for Intelligent Robots and Systems, Beijing Institute of Technology, Beijing 100081, China
[c] Key Laboratory of Biomimetic Robots and Systems (Beijing Institute of Technology), Ministry of Education, Beijing 100081, China

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ABSTRACT

The study of biomimetic robots and that of animal behaviors are mutually-reinforcing and inseparable. Animals, through long-term evolutionary processes, have developed innate advantages in locomotion, cognition, information processing and control. Inspired by their evolvement, biomimetic robots are integrated with biological characteristics which give them more powerful motor abilities, cognitive abilities and more delicate control processes than other robots. At the same time, the development of biomimetic technology and the excellent interaction characteristics of biomimetic robots also promote the study of animal behaviors. This paper aims to give a general overview of the relationship between biomimetic robots and animal behaviors. On one hand, the role of imitating animal behaviors in promoting the development of biomimetic robots is expounded from three aspects: locomotion behaviors, cognition behaviors and neural activities. On the other hand, the positive role of biomimetic robots in the research of animal behaviors is described in terms of behavioral responses of target animals, group behavioral mechanisms and cognitive neurological activities of animals. In addition, the future development of biomimetic robots and the research of animal behaviors are discussed.

1. Introduction

In the evolutionary process of hundreds of millions of years, due to the factors of genetic and variation, animals have formed advantages in execution, perception, control, information processing and organization. After a long period of natural selection, animals have possessed a high degree of rationality, scientificity and progressiveness in many aspects, such as structure, function execution, information processing, environmental adaptation and autonomous learning—the very premise for the emergence and existence of biomimetic robots. With the targets of high precision, high flexibility, high reliability, high robustness and high intelligence, the objective forces that drive the development of biomimetic robots are unstructured, unknown working environment and sophisticated, difficult working tasks. As an important member of the robot family, biomimetic robots will have more kinds and embrace more application in the future.

In recent years, with the deepening understanding of the functional characteristics and formation mechanism of biological systems, and the development of computer technology, biomimetic robots no longer remain simply duplicated biological prototypes and limited in locomotion behaviors. What's emphasized instead is that they not only have biological characteristics and locomotion patterns, but also have capacities in performance of self perception and self control etc., so as to be closer to biological prototypes. At the same time, electromechanical systems start to partially integrate with biological properties, exemplified by the fusion of traditional structures and biomimetic materials, and the application of biomimetic driving. Biomimetic robots are being developed in a life-like system with the integration of mechanical structures and biological characteristics [1].

The study of biomimetic robots and that of animal behaviors are interrelated and inseparable. Animals have to be extremely smart to survive in their environments and most of them are successful predators. The delicate structures, the principle of movements and the way of behaviors of animals have become the object of the intentional imitation of robots. Many high performance biomimetic robots which learn from the biology have then been created. The imitation of animal behaviors has resulted in technological advances that have revolutionized how manmade machines move through air, in water, and over land. The biological world still has much in the way of suggestions for how to build, design, and program biomimetic robot systems whose capabilities will far outpace what is possible today [2].

Relatively, there has been increasing use of biomimetic robots to study animal behaviors in recent years thanks to improved sophistication of robot technology and decreased costs. The use of

* Corresponding author at: Intelligent Robotics Institute, School of Mechatronical Engineering, Beijing Institute of Technology, Beijing 100081, China.
E-mail address: shiqing@bit.edu.cn (Q. Shi).

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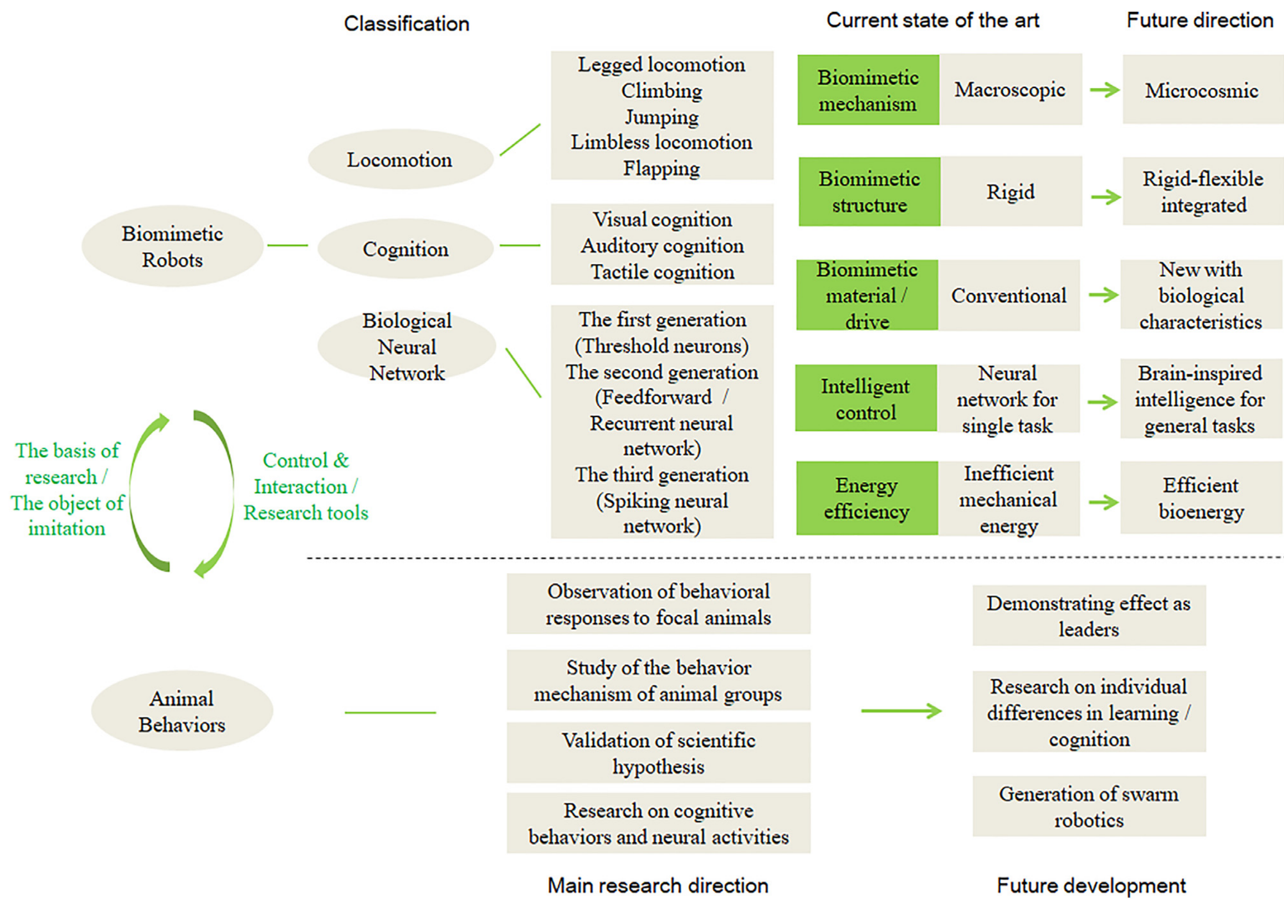

Fig. 1. Structure of the paper. The relationship between biomimetic robots and animal behaviors is demonstrated. For the study of biomimetic robots, it embodies the classification, research status and future direction. For the study of biomimetic robots to promote that of animal behaviors, main research directions and the future development are reflected.

biomimetic robots instead of living animals for the study is significant in that by ingeniously introducing some techniques, scientists have access to more useful research tools that allow for broader scope of research and easier testing of hypothesis. Besides, biomimetic robots are easier to handle than real animals and their behavioral characteristics can be accurately controlled. Biomimetic robots can also imitate complex experimental phenomena [3], or simplify the research process and reduce the cost of research [4]. Researchers cannot only control the behaviors of biomimetic robots, but also change their environment at will to make design of experiments more standardized and repeatable to carry out causal analysis of experimental phenomena [5]. Therefore, biomimetic robots have been used in much experimental research to mimic animal behaviors in a controlled way to study the focal animal response. In addition, biomimetic robots have been used as modeling tools for studying behavioral mechanisms [6]. It is worth noting that the application of biomimetic robots cannot only facilitate the study of general animal behaviors, but also has an important influence on the cognitive behaviors and the nervous systems of animals. Biomimetic robots can generate valuable insight into the function of cognitive behaviors and nervous systems [7]. Researchers use different algorithms to program biomimetic robots and compare their behaviors to those of the focal animals to understand more animal behavior rules, cognitive processes and neural activities. The deep understanding of the relationship between biomimetic robots and animal behaviors is of great importance to the research on biomimetic robots and animal behaviors and its future development.

This paper aims to make an overview of the relationship and its future development. In Section 2, the inspiration of how biomimetic robots are designed from animal behaviors in locomotion, cognition and animal neural activities is expounded. After this part comes Section 3 for the study of how biomimetic robots promote the research of animal behaviors including general behaviors and cognitive neural behaviors. Finally, the future prospect of the relationship is discussed. Structure of this paper is shown in Fig. 1 as follows.

2. From animal behaviors to biomimetic robots

2.1. Locomotion behaviors

Many animals have strong locomotion ability. By observing and simulating animal locomotion, the animal-inspired biomimetic robots are usually more maneuverable and more efficient than other robots. Locomotion types of biomimetic robots are described in legged locomotion, climbing, jumping, limbless locomotion and flapping. Fig. 2 shows biomimetic robots of the five different locomotion types.

2.1.1. Legged locomotion

Compared with most of the wheeled and tracked robots, legged biomimetic robots can traverse unstructured terrain. Legged robots may have one, two, four, six, or more legs depending on the application. Among them, quadrupedal and hexapedal robots are the most widely used in the field of bio-inspired robots. In terms of leg mechanical structure, quadruped robots usually use three kinds of

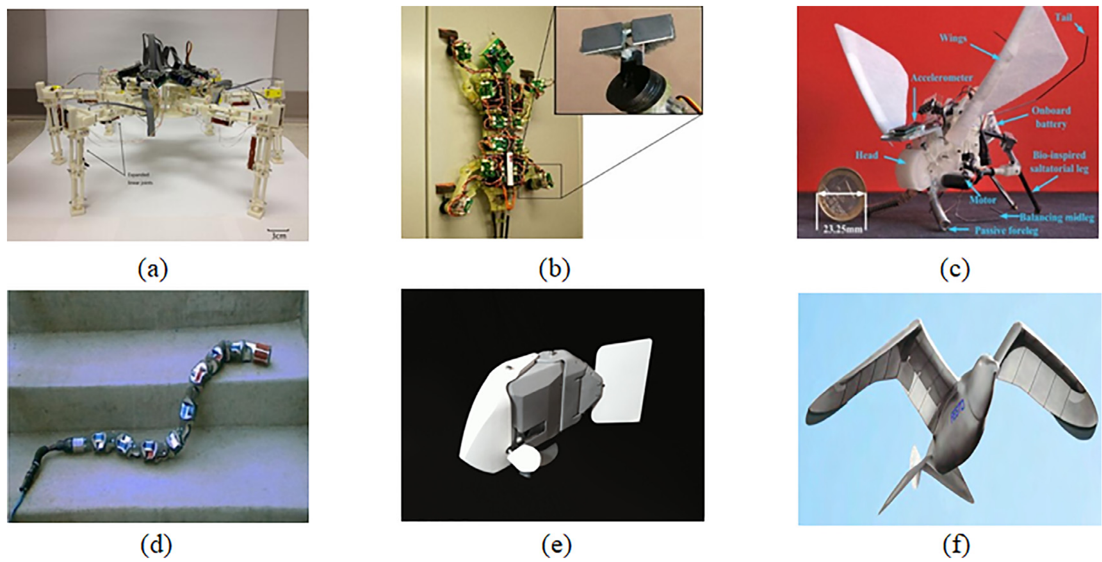

Fig. 2. Different types of biomimetic robots for simulating animal movements. (a) Hexapedal robot "SHeRo" [15]. (b) Gecko-like robot "StickyBot III" [22]. (c) Miniature bouncing robot "Grillo" [29]. (d) Snake-like robot "Unified Snake Robot" [35]. (e) Carangiform robot fish "iSplash-II" [38]. (f) Seagull-like flapping robot "Smartbird" [41].

design methods, i.e. series structure, parallel structure and hybrid structure. The leg structure of series quadruped robot is mostly open chain mechanism such as plane four bar mechanism or space four bar mechanism. The leg mechanism has large working space and high degree of freedom and allows for real time feedback on the change of position in the process of movement. This makes position repair simple. The "TITAN" series of quadruped robots developed by Tokyo Instituted of Technology [8], the "Big dog" robot (Fig. 2(a)) developed by Boston Dynamics [9], and the imitating cheetah quadruped robot designed by Ma et al. [10] all adopted the series leg structure. The parallel structure is a closed system as a whole. Closed chain mechanisms generally include four bar mechanism and swinging telescopic mechanism, featuring large bearing capacity, low energy consumption and higher precision. However, these mechanisms are also more complex and increase manufacturing costs; their flexibility and activity space lag behind those of the series structure [11]. Between the series structure and the parallel structure remains the hybrid structure which can improve the load capacity of robots to a certain extent and meet the demand of fast and stable response [12]. Gao et al. designed a hybrid leg structure for quadruped robots, and proved its feasibility and advantages through kinematics analysis and simulation [13]. Based on the leg structure and motion buffer mechanism of German shepherd dog, Shi et al. proposed a new type of single leg structure with hybrid linkage mechanism, and solved the problem of large inertia and impact of quadruped robots in the process of movement [14].

The leg structure of hexapedal robots is usually of a series joint type. The anatomy and behavioral studies of hexapod show that the legs used for walking are mainly composed of the base, the femur and the tibia so that the leg structure of the multiple hexapedal robots revolves around the base joints, the femur joints and the tibia joints respectively [15–16]. In addition, in order to simplify the structure and control of hexapedal robots or make them adapt to the specific working conditions, some hexapedal robots adopt the leg structure with a single degree of freedom [17–18].

Gait planning is the core of the research on multi legged robot control. It provides a theoretical landing point for foot trajectory planning and motion planning of the body. It also determines the timing of every foot motion and directly affects the overall motion performance of the robot. Gait planning is the key for the multi legged robot to efficiently pass the complex unstructured environment and fully display its mechanism potential. In view of the observation and experiment of animal behaviors, the multi legged robots present a periodic rhythmic gait on the flat terrain and a free gait on the rugged terrain. In the regular periodic gait, the feet are raised and dropped approximately periodically according to the specific order, and different gait movements are realized through adjustment of the duty cycle and the relative phase of each foot. For free gait planning, the gait planning method based on local rules is proposed from the perspective of imitating animal gait pattern [19]. Based on the interaction between the foot and the environment and the constraints of each foot, the biologic gait is modeled through setup of simple rules; the gait planning method based on CPG principle is proposed from the perspective of imitating the control of biological gait rhythm [20]. The feet of biomimetic robots are regarded as neurons, and their walking is realized through the periodic motion of each foot.

2.1.2. Climbing

In nature, some animals have excellent climbing ability and can climb on smooth or rough surfaces without difficulties. For animals such as geckoes, this climbing ability is achieved by adhesive force created through the use of van der Waals force in accord with their hairy pads. For cockroach and other insects, small spines on their pads are used to attach to fine concave and convex, and spines of different legs are used to climb on different surfaces. In addition, some animals such as cats and rats use claws in the pads to climb with mechanical interlocking effects. These animals usually penetrate the surface with their claws to obtain adhesive force.

Inspired by the above-mentioned animals, many climbing biomimetic robots have been developed. Menon et al. discussed the biomimetic robot based on geckoes and studied the strategic solution of geckoes for climbing. Two kinds of biomimetic adhesives were tested, and two prototypes of gecko-like robots were subsequently produced [21]. Inspired by the structures found in the toes of geckoes, Hawkes et al. developed a "StickyBot III" gecko-like robot with dry adhesives (Fig. 2(b)). This robot is closer to the real gecko in the principle of adsorption and the form of movement [22]. The climbing robot "SpinybotII" developed by Asbeck et al. is inspired by the mechanism observed from some insects and spiders; its climbing involves arrays of tiny spines on the rough surface. The robot can climb concrete, mortar, brick and masonry walls without using suction or adhesive [23]. Andrada et al. designed an adaptive lightweight climbing robot “Rat-Nic”. They tested and analyzed the motion adaptability of rats on the slope; conducted the experiment under X-ray high-speed videography and synchronized substrate reaction force measurements [24]. Ji et al. designed a climbing robot with claw-shaped flexible cushion by means of the mechanical interlocking effect of climbing animals and their theoretical analysis further revealed the mechanism of claw attachment to rough surfaces [25].

2.1.3. Jumping

The jumping biomimetic robots are motivated mainly by kangaroos in mammals, frogs in amphibians, and such insects with excellent jumping ability as fleas, locusts and so on. The jumps of long legged animals such as kangaroos, frogs, and others are based on leverage, while the jump of short legged animals such as fleas, locusts, etc. is achieved by the energy stored in a flash based on the principle of ejection. Long legged animals have a lever force that allows them to use less power to jump the same distance as short legged animals of comparable mass, whereas the short legged animals have to rely on the release of energy stored in rapid ejection [26].

Main advantages of the biomimetic jumping robots are that the range of the activity is not restricted by the objective conditions of the region and that the robots can still easily pass obstacles or ditches of several times or even dozens of times their own size when the working ground is uneven or soft. At the same time, the biomimetic jumping robots have strong explosive ability which makes them better in avoiding risks than traditional robots. Therefore, the biomimetic jumping robots with excellent environmental adaptability are very suitable for applications in interstellar exploration, disaster relief, military reconnaissance or anti-terrorist blasting. Fiorini et al. mimicked the take-off mode of frogs and developed a frog-like biomimetic jumping robot for space exploration. The robot jumps intermittently and can perform typical actions such as adjusting direction, taking off, landing and restoring posture [27]. Based on the biological structure characteristics of kangaroos, Chai et al. designed a new type of kangaroo jumping robot with the closed chain gear and five bar mechanism. By analyzing the kinematics and dynamics of the robot mechanism, they proved that the mechanism has nonlinear jumping dynamic characteristics and motion morphology similar to those of the kangaroo [28]. Li et al. found, through the observation and analysis of the bounce movement of the leafhopper, that the body acceleration is constant when the leg of the leafhopper is elongated at the take-off. Thus, a miniature bouncing robot “Grillo” was developed (Fig. 2(c)). The prototype weighs only 10 g and can achieve continuous jumping motion [29]. Based on the hind leg structure of locusts, Nguyen et al. designed a kind of locust-like jumping robot by using elastic energy storage elements. The jumping height of the robot is about 71 cm which is about 14 times the height of its own; the jumping distance is about 100 cm which is 20 times the size of its own [30]. Koh et al. used the new shape memory alloy elastic driver to replace flea muscles to store and release energy, and created a kind of biomimetic flea robot. The four bar mechanism was used to simulate the leg structure of flea. The prototype has a mass of only 1.1 g and a length of 2 cm, and the jump height can reach 30 times of its own [31].

2.1.4. Limbless locomotion

The simulating objects of limbless biomimetic robots are mainly snakes and BCF (Body/caudal fin) propelled fishes. For snakes, their basic gaits can be divided into serpentine movement, rectilinear movement, concertina movement and sidewinding movement. The serpentine movement is a gait characterized by lateral wave propagation. As the lateral wave propagates, the body moves forward, and this gait is suitable for a flat terrain. The rectilinear movement is alternating movement of the snake through the ribs and muscles to make the body move forward. This movement is suitable for narrow areas. The concertina movement, which appears to be similar to the serpentine movement, is traced forward by itself to make the body crawl forward. Snakes usually use this gait when crawling on a tree. The sidewinding movement has a spiral characteristic, which can make the body lateral or oblique movement. The most typical example is the movement gait of rattlesnakes living in deserts. This gait makes the snake more adaptable to the terrain. Researchers usually use the proposed shape curve to control the motion curve of the snake-like robot to approach the ideal shape curve. For example, the serpenoid curve proposed by Hirose et al. is used to approximate the serpentine movement [32], and Burdick et al. set up the three-dimensional motion curve in a piecewise form through analysis of the sidewinding movement [33]. Similarly, in the process of swimming, BCF propelled fishes generate propulsion waves through body fluctuations. The direction of propulsion wave is opposite to that of fish movement, and the velocity of propulsion wave is faster than that of fish body. The BCF propulsion model is subdivided into the anguillidae model, the sub carangidae model, the carangidae model, the tuna model etc., and different fish body wave equation curves are proposed to fit the corresponding motion patterns, such as the transverse body wave equation for tuna fish proposed by Donley et al. [34].

The snake-like robot is generally a high redundancy system composed of multiple joint modules. It can adapt to complex and changeable environment and perform the task of detection and rescue in the long and narrow space. Tesch et al. developed a new snake-like robot—“Unified Snake Robot” (Fig. 2(d)). The robot has 16 degrees of freedom, with orthogonal connection between adjacent joints. Each joint module is equipped with a DC servo motor, and the power output is realized through reduction gear sets. “Unified Snake Robot” can achieve serpentine movement and sidewinding movement on the ground and has the ability to overcome obstacles [35]. Liljeback et al. developed a fire rescue snake-like robot “Anna-Konda”, the first hydraulic driven snake-like robot with a large body weight of 70 kg. The joint movement of the robot is realized by hydraulic devices. Equipped with two nozzles on the head, the robot can extinguish distant sources of fire in experiments [36]. Zarrouk designed a single drive snake-like robot, “SAW”. The most distinct feature of the robot is that only one motor is used to drive the robot to achieve the snake-like movement. Ingeniously structured, the robot can transform the space spiral movement into plane wave movement [37].

Compared with other underwater vehicles, the BCF propelled biomimetic robotic fish has the advantages of fast moving speed, high efficiency and quick starting performance, thus suitable for the occasion of long-time, long-distance, high-speed swimming or instant accelerating or steering. Clapham et al. developed a new carangiform robot fish “iSplash-II” (Fig. 2(e)) which shows fast swimming speed and strong stamina. The robot fish has a length of 32 cm, and its swimming speed can reach 116BL/s (i.e. 3.7 m/s) when the swing frequency is 20 Hz. A new mechanical drive system has been designed to effectively transmit large forces at high frequencies for high-speed propulsion [38]. Li et al. introduced a soft electronic fish with fully integrated circuit board and remote control system. Without any motor, the robot fish is driven by a single actuator to drive a soft electroactive structure made of dielectric elastomers and ionic conductive hydrogels. The electronic fish can swim at the speed of 6.4 cm/s, much faster than that of the cordless soft robotic fish driven by soft response materials [39].

2.1.5. Flapping

Birds, insects and bats in mammals have adapted to the environment and evolved to reach almost perfect degree in the form, movement mode and energy utilization that provide references for the design of the flapping biomimetic robots. Through the study of the biomimetic mechanism and flapping structure of flying animals, many exquisite structures of flight, as well as the mode of flapping movement, such as flapping frequency and flapping amplitude, are recognized. For the biomimetic flapping flying robots, they usually have the advantages of flexibility, high efficiency and reliability. Pornsin-Sirirak et al. developed a “MicroBat” flapping micro aircraft. The wing structure made by MEMS technology imitates that of the bat. It is the earliest electric flapping aircraft with the biological flight mode. The maximum flight time of the prototype is 42 s [40]. Mackenzie developed a seagull-like flapping robot “Smartbird” (Fig. 2(f)) made in carbon fiber materials. The robot has flexible wings and a mass of only 450 g. Through the delicate transmission structure of multi rod linkage, the researcher realized wing folding and flapping movement similar to that of the real seagull, and the angle of the flapping wing can also be changed according to the demand. These improvements greatly increase the flight efficiency [41]. The machine fly designed by Ma et al. is a typical biomimetic flying robot with a mass of only 80 mg and a wingspan of only 3 cm. Its flight principle is very similar to that of a real fly. The power consumption of the flying robot is about 19 mW, roughly the same as the consumption of real flies [42].

In addition, MPF (Media/paired fin) propelled fishes flap with a pair of pectoral fins or other fins to produce propelling force. They have high propulsion efficiency when swimming slowly with high stability and strong anti-interference ability. Therefore, some underwater flapping biomimetic robot fishes have been developed. The biomimetic manta ray prototype “RoMan-II” developed by Zhou et al. has 6 flexible fin rays on both sides of the fish body and propelling force can be generated with the flapping of the fin rays. The robot fish can achieve maneuverability in all directions and complete difficult movements such as the spot turn and the straight back. The stable cruise speed of the robot fish is 0.5 m/s [43]. The prototype of biomimetic cow-nosed ray developed by Cai et al. is driven by fin rays. 3 pairs of fin rays are arranged on both sides of the body; each fin ray is driven by a servo motor. The speed of the robot fish is about 0.26 m/s through swimming test in the pool [44].

2.2. Cognition behaviors

Studying how biological systems process sensory information to obtain design inspiration can lead to continuous innovation in cognitive aspects of biomimetic robots. Through long-term evolution, many animals have developed unique cognitive styles that make them the object of researchers for learning and imitation. Sensory information is sampled and processed in parallel with dozens or even hundreds of receptor organs, which improves the signal to noise ratio by averaging and reduces the possibility of errors caused by the loss or failure of a receptor organ [45]. The cognitive system of biomimetic robot usually has the advantages of low energy consumption, high sensitivity and redundancy. Fig. 3 demonstrates some representative results of biomimetic technology in the field of robot cognition.

2.2.1. Visual cognition

In the sense of visual cognition, biomimetic technology is generally applied to bionic eyes, navigation and positioning of robots. The compound eyes of insects which have a powerful field of view without angular distortion enlighten the development of bionic eyes. A hemispherical compound eye designed by Song et al. combines elastic composite optical devices with deformable arrays of thin silicon photodetectors and can be formed into a hemispherical body to capture a wide field image [46]. Floreano et al. developed a semi-cylindrical compound eye made of a composite optical layer (Fig. 3(a)). It can extract optical flow faster than insects [47]. A compound eye composed of three ocelli has been added to an insect-size flying robot to verify the hypothesis that some insects can use visual information instead of angular acceleration to stabilize flight [48]. Effective cognition of space environment is an important ability for animals to survive. The damage experiment showed that hippocampal formation is the key brain area of environmental cognition and episodic memory. Milford et al. applied the results of neurobehavioral research to model the “position and posture cells” of rats. With the use of the vision-driven navigation system, a RatSLAM biomimetic navigation algorithm was built for real-time positioning and map building [49–50]. Tian et al. used the CAN (competitive attractor network) model to construct the cognitive map based on the RatSLAM algorithm, and proposed a cognitive map building and navigation system for mobile robot with RGB-D sensor [51]. Besides, to provide more flexibility with new mechanical structure and the corresponding control strategies, Qiao et al. deeply investigated the vision, motion, planning, emotion, energy and integration of biological systems. They developed a series of bio-inspired vision and planning models [52–53], and proved their effectiveness in visual cognition and motor learning. Their results provide a new way for robotic sensorimotor modeling and structure design.

2.2.2. Auditory cognition

In the sense of auditory cognition, biomimetic technology is mainly used to achieve the tasks of recognition and localization. Inspired by cricket’s homotaxis, Horchler et al. developed a sound localization system on the platform of autonomous outdoor robot. The robot has been shown to recognize simulated male cricket songs on natural terrain [54]. Based on the morphological and functional principles of the dolphin’s lower jaw, Dobbins developed a new sonar receiver to provide a high resolution output in shallow water with the use of an end shooting array in a single pulse mode to simulate the angle positioning [55]. Zu et al. studied the acoustic environment mobile robot navigation system based on the biological auditory perception mode, and realized target localization based on bionics through auditory sensors. The validity of the auditory perception module is verified by the experiment of acquiring sound location information [56]. Following the mapping module of RatSLAM, a navigation model based on BatSLAM algorithm was proposed by Steckel et al. to perform the task of simultaneous localization and mapping on mobile robots through biomimetic sonar [57].

2.2.3. Tactile cognition

In the sense of tactile cognition, biomimetic technology is commonly applied to artificial skins, whiskers or cilia perception and the simulation of tactile nerves. Giacomo et al. demonstrated the sensing mechanism of pectin films mimicking pit membranes and recorded their properties. These membrane surfaces have a sensitivity of at least 10 MK at a wide temperature range (45 K), and have very high responsiveness in that a warm object can be detected at a long distance. The prepared material can be used as a layer in the artificial skin platform which improves its temperature sensitivity to achieve the best biological performance [58]. Liu et al. chose polyvinylidene fluoride (PVDF) film as a sensing element because of its flexibility, high sensitivity and easy integration in different shapes (Fig. 3(b)). A four stage micro robot with sensing skin has been developed. Experiments on the separate sensing silicone segments show that the biomimetic PVDF sensors can detect external contact and internal action, thus imitating the exteroceptive and proprioceptive capabilities of real earthworms [59]. For whiskers perception of biomimetic robots, strongly inspired by the vibrissal system of small mammals, the research mainly focuses on extracting the object properties from whisker-surface contacts,

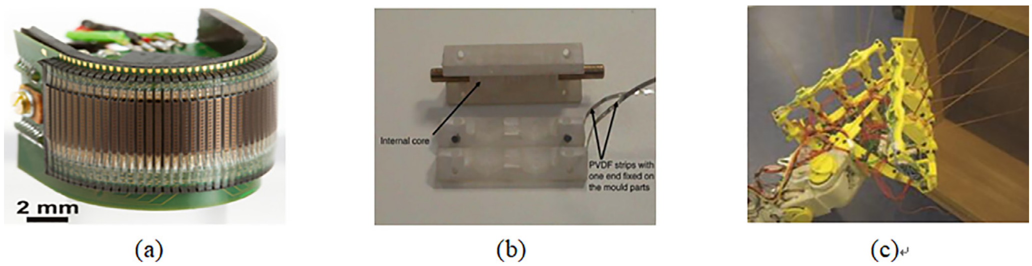

Fig. 3. Applications of biomimetic technology in the field of robot cognition. (a) A semi-cylindrical compound eye developed by Floreano et al. [47] which can extract optical flow faster than insects. (b) Sensing skin developed by Liu et al., with the use of polyvinylidene fluoride (PVDF) film [59], which can detect external contact and internal action. (c) Whiskers perception of the biomimetic robot "SCRATCHbot" in [61]. The platform is used to study the perceptual noise elimination and three-dimensional orientation of biomimetic models.

controlling the whiskers and studying the impact of such control on sensing (Fig. 3(c)) [60-62]. Based on the biomimetic cilia-based cupula receptor, a kind of lamprey robot with biomimetic sensing capability is designed. The low-cost flexible/compliant biomimetic cilia can detect the velocity of the medium jet from 0.05 m/s to 0.6 m/s and thus meet the movement needs in the unstructured environment [63]. Kim et al. used flexible organic electronics to simulate the function of tactile nerve. The artificial afferent nerve collects pressure information from the pressure sensor cluster, converts the pressure information into action potential with a ring oscillator and combines the action potential of multiple oscillators with a synaptic transistor. The biomimetic hierarchical structure can detect the movement of objects and distinguish braille characters combined with pressure input. The biomimetic tactile nervous system has potential applications in neuromechanics and neuroprosthetics [64].

2.3. Neural activities

Many animals rely on powerful brain functions, with the ability of perception, learning, memory, emotion, decision and so on. As the brain models of various animals and working mechanisms of these functions are studied, the design of biological neural network is of great significance for the future development and intellectualization of biomimetic robots. Compared with other control methods, the biological neural network with brain-inspired intelligence has stronger capacity in autonomous learning and self-adaption. It also has good robustness and low energy consumption when dealing with complex tasks.

2.3.1. Evolution of biological neural network

Connectionism, represented by artificial neural networks, begins with the preliminary simulation of the cerebral nervous system structure and its computer mechanism. The first generation artificial neural network is composed of threshold neurons and remains a very simple model in concept. If the sum of the weighted input signals exceeds the threshold, the neuron will send a binary "high" signal. Although they can only give digital output, these neurons have been successfully applied to powerful artificial neural networks, such as multilayer perceptrons and Hopfield networks. Neurons of the second generation do not use the step length or threshold function to calculate their output signals, but a continuous activation function that makes them fit for analog input and output. Typical examples of neural networks composed of these types of neurons are feedforward and recurrent neural networks. They can approach any function and hence can be used for computation. The actual neuron has the basic transmitting frequency, and these intermediate output frequencies can be simulated by the continuous activation function. Therefore, the second generation neurons are more biological and powerful than the first generation neurons. The third generation of neural networks improves the level of biological realism with the use of individual spikes. These neurons, just like real neurons, allow time and space information to be added to communication and computation. Instead of using rate coding, they use pulse coding—just like biology which can respond quickly to external stimuli because the information transmission of the biological neural network depends on the specific pulse time, a more efficient encoding method [65-66].

2.3.2. Development on construction and algorithm

In terms of the construction and algorithm development of biological neural network, some representative studies have been done as follows. For RNNs, due to the large scale of the network and the high cost of monitoring network output, it is difficult to fully access the state of neurons, and this makes the analysis of real-time dynamic behavior difficult. Therefore, some creative work has been done to solve the problem of event-triggered state estimation of neural networks and save resources and improve energy efficiency at the same time. Liu et al. investigated the event-triggered $H\infty$ state estimation of discrete-time stochastic memristive neural networks (DSMNs) with time-varying delays and missing measurements [67]. Shen et al. studied the event-triggered state estimation of discrete-time multi-delay neural networks with random parameters and incomplete measurements [68]. Wang et al. considered event-based finite-time state estimation for discrete-time stochastic neural networks with mixed discrete and distributed delays [69-70]. Liu et al. studied the partial-nodes-based (PNB) state estimation problem for complex networks with unbounded distributed delay and energy-bounded measurement noise [71]. The above theoretical results have been verified by numerical examples. Williamson et al. described a biological neural network contained in cephalopod statocysts. The statocyst network consists of only a small number of cells, but a large number of efferent innervations from the brain to form an "active" sensory organ which uses feedback and feedforward mechanisms to dynamically regulate intracellular activity and interconnectivity of various components. The system provides an excellent model to describe the operation mechanism of complex neural networks [72]. According to the experimental results, signal transmission and neuronal energy requirements are tightly coupled with the encoding of information in the cerebral cortex. Wang et al. proposed a new scientific theory which provides a unique mechanism for brain information processing [73]. Since it bridges the gap between functional connectivity and energy consumption in biological neural networks, the energy coding theory may play an important role in the quantitative study of cognitive function. Bonabi et al. put forward a design scheme of biological neural network using FPGA based on Hodgkin Huxley neuron model. Adding the inherent attributes of FPGA such as parallelism and re-configurability makes the FPGA-based biological neural network an effective tool for the study of neural control of cognitive robots and systems [74]. Zhang et al. proposed that the spike training data of multiple neurons can be used as an alternative source to predict neural network structure. Based on the structure of predictive neural network and

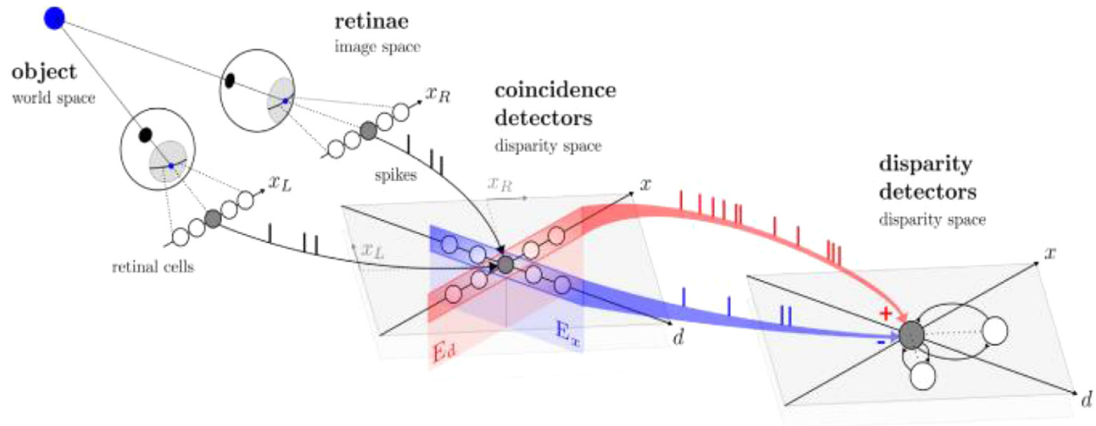

Fig. 4. A biological neural network model for three-dimensional visual perception in [82]. An object is perceived by two eyes and projected onto their retinal cells. The spiking output of these cells integrates the temporal and spatial information. The final output is the coded representation of the original scene in the parallax space.

the spreading activation theory, a spike prediction method is proposed. Prediction of neural network structure and neuron activities can be used as bases to explore the simulation of brain-inspired intelligence [75]. Combining adaptive control theory with efficient coding theory, Denève et al. pointed out that neural circuits can learn complex dynamic tasks with local synaptic plasticity rules. The resulting biological neural network can learn any dynamical systems and produce irregular spike sequences as variables, just as observed in experiments. This change in single neuron may hide a very effective and powerful computing capability [76].

2.3.3. Application of biological neural network

In the application of biological neural network, the tasks of data classification, cognition, path planning and navigation are hot spots for researchers. With the use of various methods of information coding and network design, the classification ability of biological neural networks trained by unsupervised learning methods has been tested on commonly used benchmark datasets, and satisfactory results have been achieved [77-79]. For image recognition, biological neural networks are usually used for image classification and visual object detection in complex intensity images, image compression and reconstruction (Fig. 4) [80-82]. A model of antennal leaves of the locust proposed by Martinez et al. has been implemented in a spiking neural network and used in tracking experiments in which mobile robots are assumed to be close to odor sources. A frequency adaptation has been used for temporal evolution of spatial coding to enhance the distance between representations of similar odors [83]. Hong introduced an improved SpikeProp learning algorithm which achieved better learning stability under different activities. The network incorporates biological reality features such as horizontal connections and sparse activities. With the system universal to a certain extent, different types of cognitive tasks such as MNIST digital recognition, spatial coordinate transformation, and motor sequence generation can be accomplished with different temporal codes [84]. Moreover, the biological neural networks have been successfully applied to path planning, navigation, trajectory tracking and detection of biomimetic robots, and have played an important role in the control field of biomimetic robots [85-88].

Table 1 shows representative references on biomimetic robots, and their main contributions are pointed out.

3. Biomimetic robots for the study of animal behaviors

As more and more biomimetic robots have been developed with the inspiration of various animals, the ability of these biomimetic robots to learn, adapt to the environment and interact with the environment has also been significantly improved. On one hand, the progress is conducive to the development of the robot system itself. For example, Qiao et al. discovered the wide existence of "Attractive Regions in Environment (ARIE)" in a new space in robotic manipulation [89] which was reported as Qiao's concept. Their series work [90-91] in this area provides an important new way for robotic system to use environment information for high precision manipulation, and has proven to be useful in industry. It also provides powerful tools for the study of animal behaviors. Specifically, a new approach based on biomimetic robots instead of real animals is developed for the study on the animal responses to stimuli from conspecifics or heterospecifics. In fact, biomimetic robots are controllable and repeatable. They can provide access to variables or quantities that are difficult to measure on animals, perform dangerous tasks, and realize systematical change of their shapes [92]. Biomimetic robots are becoming an important scientific tool for studying animal behaviors; their application has also promoted the understanding of a wide range of animal behaviors.

3.1. Observation of behavioral responses to focal animals

Through some effective control methods, biomimetic robots can imitate the behaviors of animals and interact with animals through active guidance to observe and record responses of focal animals. Behavior patterns or mechanisms of animals hence are furthered studied. Shi et al. developed WR series of robotic rats. These robotic rats can imitate the rearing, mounting, and body-grooming actions of real rats and study different types of behavioral responses (tension, friendliness, neutrality) of rats by tracking and contacting the target. Experiments show that robotic rats can regulate rat behaviors in a controllable and predictable way. By interacting with multiple rats, the robots also provide a new way to shape the sociality of animals living in groups (Fig. 5) [93-96]. Son et al. studied the interaction between a kind of biomimetic robot and biological insects in an adjustable space. The robot propagated specific odors to attract insects indirectly and guide them to a predetermined trajectory. The behavior of insects is relatively simple, making the interaction relatively easy [97]. Kopman et al. studied the response of zebrafish to a robotic fish. The robotic fish is similar to the real zebrafish in shape and color. Experimental results show that response of the zebrafish changes correspondingly with the change of the tail-beating motion pattern of the robotic fish. The preference and behavior of zebrafish depend on whether the tail-beating frequency of the robot fish is controlled by the

Table 1
Representative references on biomimetic robots.

Reference	Biomimetic object	Research content	Main contribution
Raibert et al. [9]	Dog(Legged locomotion)	Electromechanical integration, dynamic control	Traversing rough terrain
Chen et al. [16]	Insects(Legged locomotion)	Compliant leg mechanism, motion planning	Crossing rugged terrain, reducing impact
Hawkes et al. [22]	Gecko(Climbing)	Two foot mechanisms, synthetic dry adhesives	Climbing steadily on a flat surface
Ji et al. 2018 [25]	Cat(Climbing)	Adhesion mechanism of claw, structure design of flexible claw	Fast climbing on vertical rough surface
Li et al. [29]	Insects(Jumping)	Theoretical analysis of jumping dynamics, jumping leg mechanism	High dynamic similarity, continuous jumping
Koh et al. [31]	Flea(Jumping)	Springing mechanism driven by SMA	Light structure, high energy efficiency, fast jumping
Zarrouk et al. [37]	Snake(Limbless locomotion)	Two-dimensional kinematics analysis, wave structure design	Single motor drive, motion generated by continuous forward wave
Li et al. [39]	Fish(Limbless locomotion)	Soft robotic fish driven by dielectric elastomer	Swimming faster than other soft robotic fish; long durability and temperature tolerance
Ma et al. [42]	Fly(Flapping)	Flexure-based sub-millimeter mechanisms, modular flight control	Achieving stable hovering and basic flight maneuvers
Cai et al. [44]	Cow-nosed ray(Flapping)	Biomimetic feature extraction, flapping wing structure design	Achieving flapping motion with simple mechanical structures
Floreano et al. [47]	Fruit fly(Compound eyes)	Hierarchical design method of biomimetic compound eye	Low power consumption, high temporal resolution, local light adaptability
Qiao et al. [52]	Primate(Visual cortex)	Introduction of memory and association mechanism in HMAX model	Reducing computation storage, good recognition performance
Dobbins [55]	Dolphin(Lower jaw)	Dolphin echolocation receiving mechanisms, new sonar receiver	Angular positioning, high resolution output
Steckel et al. [57]	Bat(Hippocampus)	Model for sonar based spatial orientation and map building	Mapping unmodified environments efficiently by biomimetic navigation model
Prescott et al. [61]	Rat(Whiskers)	Morphological and mechanical modeling analysis of whiskers	Establishment of rat whisker sensory system
Kim et al. [64]	Cockroach(Afferent nerve)	Simulation of sensory nerve with flexible organic electronics	Object motion detection, braille characters discrimination
Shin et al. [81]	Biological neural network	Novel partial occlusion and rotation image recognition system	Better performance than recognition system based on support vector machine
Martinez et al. [83]	Locust(Antennal lobe)	Simplified biomimetic model of locust antenna lobe with spiking neural network	Frequency adaptation, enhancing the distance between representations of similar odors
Yang et al. [85]	Biological neural network	A method of topological structural neural network	Planning collision-free complete coverage robot paths
Yang et al. [87]	Biological neural network	Tracking control of mobile robot based on neurodynamics	Smooth continuous control signal, handling situations with large tracking errors

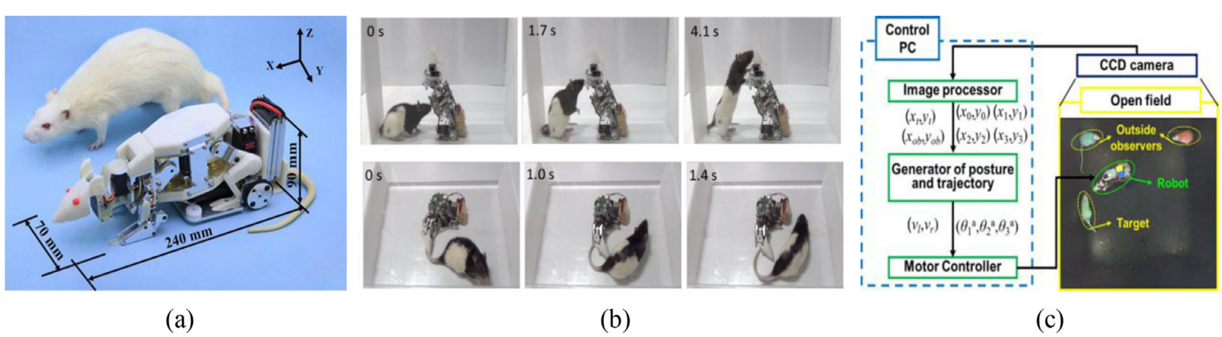

Fig. 5. Biomimetic robotic rat and the interaction between the robotic rat and experimental rats. (a) Comparison between the robotic rat WR-5 and a real adult rat [94]. (b) The robotic rat can produce movements similar to experimental rats, including pitch movement and yaw movement [95]. (c) Interaction experiments between the robotic rat and experimental rats [94].

function of zebrafish motion and how this control is implemented [98]. Similar studies have also been carried out on other animals such as frogs [99], squirrels [100-101], cows [102] and honeybees [103] through control of biomimetic robots to give animals a certain stimulus or enticement to observe the responses and behaviors of focal animals.

3.2. Group behavior research and hypothesis validation

In order to further research the underlying mechanism of animal behaviors, biomimetic robots are usually placed in a group of animals to explore animal behavior patterns or validate scientific hypotheses in the interaction process. Halloy et al. put special designed biomimetic autonomous mobile robots into cockroaches. A mixed group was released into two shelters with different opacity to study the collective decision-making behavior of cockroaches in shelter selection (Fig. 6) [104]. In a study of fish decision-making behavior, remotely controlled robotic fishes were thrown into a school of fishes, and experiments showed that the path chosen in the Y-maze was based on a quorum [105]. Gribovskiy et al. developed a biomimetic mobile robot to study the behavior of chickens. The robot can benefit from the positive feedback mechanism that plays a key role in animal collective behaviors [106]. Accepted as being homogeneous and capable of interacting with chickens, the robot serves as an effective tool for studying the behavioral mechanism of poultry especially in collective and social behaviors. In

Table 2
Representative references on the application of biomimetic robots to animal behavior research.

Reference	Research object	Research content	Main contribution
Shi et al. [93]/[96]	Rat	Behavioral response of rats to a robotic rat during multi-rat interaction	Regulating the behavior of rats, shaping the sociality of animals
Son et al. [97]	Insect	Insect heading recognition, transmission of specific odors	Inducing insects to move along a given trajectory
Kopman et al. [98]	Zebrafish	Responses of zebrafish to a robotic fish	Different responses of zebrafish to the tail-beating patterns
Landgraf et al. [103]	Honeybee	Establishment of a biomimetic robot imitating known signals	Biological experiments with the robot on honeybee dance communication system
Halloy et al. [104]	Cockroach	Collective decision-making by mixed groups of cockroaches and robots	Research and control of self-organizing behavior patterns of social animals using biomimetic robots
Gribovskiy et al. [106]	Domestic chicken	Development of autonomous biomimetic robot, group behavior of domestic chicken	Socialized integration of robots into animal groups
Faria et al. [109]	Fish	Two kinds of interaction between a robotic fish and a shoal of fish	Evidence of the effectiveness of biomimetic robotic fish in the study of fish behavior
Frohnwieser et al. [110]	Multiple species of animals	Description of cognitive behavior research of animals with biomimetic robots	Using robots to insight animal cognitive behavior in experiments
Jeong et al. [112]	Fronto-parietal networks in animals brain	New model for integrated learning of prospective visual attention and sensorimotor control	Confirmation of premotor theory of visual attention by the experiment of neuro-robot
Margerie et al. [113]	Quail chick	Tests of spatial cognitive behavior of chicks	Better spatial ability and more desire to explore in feeding conditions of mobile heating robot

Fig. 6. The study of collective decision-making behavior of cockroaches in shelter selection [104]. The two shelters are made of plastic plates covered with red film filters, and the darkness is controlled by the number of covered filters.

some cases, hypothetical models of animal behavior patterns have been proposed, but there lack empirical data and related experimental tests. Biomimetic interactive robots can be used to evaluate these models and hypotheses [107]. For example, in the debate on modeling fish collective behavior, some researchers proposed metric interactions, while others proposed topological models. To verify these two model predictions, a robotic fish was used to perform sudden changes in direction relative to other shoals. The behavioral responses of shoal members revealed that a topological model is more realistic [108-109].

3.3. Research on cognitive behaviors and neural activities

Other than animal behaviors in general, cognitive neuroscience increasingly benefits from biomimetic robots. The key features of biomimetic robots can be manipulated systematically to explore the development of perception, cognition and neuroscience of animals in a repeatable and comparable manner [110]. By dynamically simulating the spiking neurons, a hypothesis about the recognition of conspecific songs by crickets was proposed and verified by a biomimetic robot which can produce highly similar behaviors to crickets. Many biological properties can be observed in constructed artificial neural circuits which correspond to the neurophysiology of crickets, including distinct "recognition neurons" [111]. Jeong et al. proposed a new model for integrated learning of prospective visual attention and sensorimotor control. This model uses the multiple timescales recurrent neural network (MTRNN) which can correspond to the frontal-parietal lobe network in the cerebral cortex. The experiments on multi-object processing by biomimetic neuro-robotics show that a certain degree of generalization can be achieved in terms of position and object size changes [112]. Robots can also be used to study the ontogeny of animal cognition and behavior characteristics. In theory, it is possible to achieve complete control of an animal by exposing it to one or more biomimetic robots from birth. For example, compared with birds exposed to a fixed heater, Japanese quail chickens, raised with a mobile heated robot that mimics a hen, exhibit better spatial capabilities and more desire to explore [113]. Therefore, small differences in feeding conditions have a profound impact on the development of key cognitive skills.

Table 2 shows representative references on the application of biomimetic robots to animal behavior research, and their main contributions are pointed out.

4. Development and trends

The relationship between biomimetic robots and animal behaviors has become increasingly close, and the two will mutually promote and integrate with each other for complex research in their respective fields. For biomimetic robots, their structures, materials and drives will be further integrated with biological characteristics. Biomimetic structures will be developed from rigid structures to rigid-flexible integrated structures which have both rigid supporting structures and flexible adaptive structures. As a result, the biomimetic mechanism will become lighter, more precise and adaptable to different environmental constraints. Traditional materials such as steel and plastics will be gradually less used in biomimetic robots; biomimetic materials instead will be more frequently used because they are closer to biological performance with low energy consumption, high efficiency and powerful adaptability to the environment. Biomimetic materials can achieve miniaturized electromechanical systems, such as micro air vehicles and unconventional sensors, and greatly promote the development of software robots [114]. In the aspect of driving, biomimetic robots will more adopt the artificial muscle and other biomimetic driving forms to realize the integration with structures and materials so that they are closer to the animals being imitated [115]. In the aspect of biomimetic mechanism, the research will not be limited to the macro level, but develop across the macro, micro and even nano scales from the surface to the inside in a gradually thorough manner. With more realistic mathematical models established, it will provide further theoretical basis for the design of biomimetic robots. In terms of control, micro-electromechanical and physicochemical properties of biological systems of biomimetic robots will be further studied. There will also be more use of biomimetic control methods such as EMG signal control and EEG signal control on the basis of existing research [116]. The neural networks are used to control the biomimetic robots to achieve more precise and adaptable control process with faster response. In addition, as brain-inspired intelligence further develops, biological neural network is no longer limited to a certain type of specific tasks, but can achieve complex multi-task processing with a certain degree of versatility [117]. In terms of energy efficiency, most biomimetic robots suffer from the problem of low energy efficiency, and there lacks effective research on the use of biological energy. Even for intelligent control systems, complex artificial neural networks also consume a large amount of energy that far exceeds the power consumption volume of animal brains. It is one of the future research hotspots to deepen the research on mechanism of bioenergy conversion and higher energy efficiency [118]. In short, in the future, inspired by the animal behavior mechanisms, biomimetic robots will no longer simply imitate a certain behavior pattern, but will develop with multi-degree of freedom and multi-function models that combine perception, movement and neural intelligent control to simulate various animal behaviors or complete various kinds of complex tasks.

As technology continues to progress and the manufacturing cost declines, biomimetic robots will play an increasingly important role in the research of animal behaviors. In recent years, the cross discipline of imitation and social learning in robots and animals has emerged. Biomimetic robots act not only as observers of the behavioral responses of target animals, but also leading producers of demonstration effects. They can actively guide the animal groups to produce certain behaviors that researchers have planned beforehand for better study of the social behaviors of animal groups. Against this background, swarm robotics came into being. Swarm robotics is a rapidly expanding field of research that provides some interesting perspectives for studying the social behaviors of animals. Its automatic identification of social behaviors allows for evaluation on the behavior repertoire of an individual or species and calculation of the transfer probabilities between different behaviors. The robotics thus can help develop dynamic models of animal behavior structures which robots can represent. Besides, through mutation and evolvement of the social behaviors of robots, swarm robotics will also promote the study of evolutionary processes and thus provide new predictions for the study of communication and adaptive behaviors [119-120]. Moreover, biomimetic robots are used to study the differences in learning or cognitive styles and degrees of individual animal, which is also one of the future research trends.

5. Conclusion

Starting from the relationship between biomimetic robots and animal behaviors, this paper focuses on how biomimetic robots can obtain inspiration from animal behaviors for design and innovation to constantly improve the performance of biomimetic robots and enhance their role in promoting animal behavior research. In addition, future prospects of the research on the relationship are described. It should be firmly believed that with the continuous development of biomimetic technology, the connection between biomimetic robots and animal behaviors will get closer and the two fields of study can thus benefit from each other and progress together. This is a precious treasure that nature presents us.

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Zihang Gao received the B.S. degree in Mechanical Engineering and Automation from Tianjin Polytechnic University, Tianjin, China, in 2013, and the M.S. degree in Mechatronic Engineering from China University of Mining and Technology (Beijing), Beijing, China, in 2017. He is currently working toward the Ph.D. degree in Mechanical Engineering from Beijing Institute of Technology, Beijing, China. His research interests include biomimetic robotics, neural networks and artificial intelligence.

Qing Shi received the B.S. degree in Mechatronics from Beijing Institute of Technology, Beijing, China, in 2006, and the Ph.D. degree in Biomedical Engineering from Waseda University, Tokyo, Japan, in 2012. He had been a Research Associate at GCOE Global Robot Academia of Waseda University from 2009 to 2013. He is currently an Associate Professor at Beijing Advanced Innovation Center for Intelligent Robots and Systems, Beijing Institute of Technology. His research interests are focused on biomimetic robots, computer vision, and micro/nano robotics.

Toshio Fukuda received the B.S. degree from Waseda University, Tokyo, Japan, in 1971 and the M.S. and Ph.D. degrees from the University of Tokyo, Tokyo, Japan, in 1973 and 1977, respectively. From 1977 to 1982, he was with the National Mechanical Engineering Laboratory, Tsukuba, Japan. From 1982 to 1989, he was with the Science University of Tokyo. Starting in 1989, he was with Nagoya University, Nagoya, Japan, where he was a Professor with the Department of Micro System Engineering, and a Professor with Meijo University, Nagoya Japan. He is currently a Professor (1000 Foreign Experts Plan) with the Intelligent Robotics Institute, School of Mechatronic Engineering, Beijing Institute of Technology, Beijing, China, where he is mainly engaged in the research fields of intelligent robotic systems, cellular robotic systems, mechatronics, and micro/nano robotics. Prof. Fukuda is 2019 IEEE President-Elect and Director of Division X: Systems and Control (2017–2018), and he was the President of IEEE Robotics and Automation Society (1988–1989), Editor-in Chief of IEEE/ASME Transactions on Mechatronics (2000–2002), Director of Division X: Systems and Control (2001–2002), IEEE Founding President of Nanotechnology Council (2002–2003, 2005) and Director of Region 10 (2013–2014).

Chang Li received the B.S. degree in Mechanical Engineering and Automation from the Northeastern University at Qinhuangdao, Hebei, China, in 2014. He is currently working toward the Ph.D. degree in Mechanical Engineering from Beijing Institute of Technology, Beijing, China. He was a Special Research Student at Waseda University, Tokyo, Japan, from 2017 to 2018. His research interests include biomimetic robotics, computer vision.

Qiang Huang received the B.S. and M.S. degrees in electrical engineering from the Harbin Institute of Technology, Harbin, China, in 1986 and 1989, respectively, and the Ph.D. degree in mechanical engineering from Waseda University, Tokyo, Japan, in 1996. In 1996, he joined the Mechanical Engineering Laboratory, Tsukuba, Japan. He was with the University of Tokyo, Tokyo, Japan, from 1999 to 2000. He is currently a Professor and the Director of Intelligent Robotics Institute, and the Director of the Key Laboratory of Biomimetic Robots and Systems, Ministry of Education of China, and the Executive Director of Beijing Advanced Innovation Center for Intelligent Robots and Systems, and the Vice Director of the Key Laboratory of Intelligent Control and Decision of Complex System, Beijing Institute of Technology, Beijing, China. His current research interests include biorobotic systems and human–robot fusion systems.