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REVIEW PAPER

Review of Bionic Crawling Micro-Robots

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Abstract

This article introduces and explores the current frontier four-legged (quadruped) and six-legged (hexapod) crawling micro-robots. The performances of various crawling micro-robots are compared, and their driving modes are analyzed. Moreover, the research status of crawling micro-robots is summarized, and the future application prospects and development directions of these robots are put forward.

Keywords Crawling micro-robot · Piezoelectric actuator · Shape-memory alloys · Micromotor

1 Introduction

Robotics technology integrates the knowledge of materials, machinery, electronics, sensors, computers, artificial intelligence, and many other disciplines, and involves numerous cutting-edge technologies. Intelligent crawling micro-robots based on biomimetic mechanisms have become a research hotspot in recent years. As a new topic in the field of robotics, bionics and its related application technologies are based on the study of the mechanisms of the outstanding functions of specific animals in a certain aspect, and bionic robots that can replace humans have been created for use in harsh environments. These new research topics have attracted numerous researchers, and numerous results have been produced. With the vigorous development of robotics-related fields, such as new materials and artificial intelligence, micro-robots based on bionic technology will be prevalent in the future.

Due to their small size, micro-robots can pass through narrow places, such as inside water pipes [1], gas pipes [2–4], and even the human body [5]. Numerous studies have been conducted in the field of biomimetic micro-robots [6–13], and most of the related work is concentrated on the centimeter-level mesoscale. Due to their low power requirements, micro-robots can use environmental energy sources, such as light, electric fields, magnetic fields, or vibration [14, 15], as their power supply. Furthermore, their small size also reduces their cost and increases the possibility of using disposable robots that can be destroyed [16]. With the advancement of technology, smaller and more powerful electronic and mechanical components can be fabricated, which will enable the construction of more miniature robots.

Crawling robots have always occupied a pivotal position among the numerous types of micro-robots due to their simple modification and high application value. Crawling micro-robots are small, sometimes invisible, and disposable, and have the potential to operate in small, dangerous places that humans and large machines cannot reach. Therefore, they are suitable for application in military reconnaissance, infrastructure and equipment monitoring, micro-component nano-processing, and possibly medicine [17, 18]. In the past two decades, many excellent crawling micro-robots (ranging from tens of cm^3 to a few mm^3 in volume) have emerged. At

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present, the maturity of research on crawling micro-robots far exceeds that of other types of robots. The most popular structures of crawling micro-robots are four-legged (quadruped) and six-legged (hexapod) structures. While quadruped crawling micro-robots were developed early and have achieved excellent performance, their structure is not very stable. In contrast, hexapod robots, which are designed based on the structures of insects found in nature, have good adaptability to multiple terrains, and are more suitable for special environments, such as those related to exploration and remote control. However, there are relatively few research results regarding hexapod crawling micro-robots.

From the perspectives of their motion structure (including the mechanical structure and gait) and driving mode, this review analyzes the current exceptional quadruped and hexapod crawling micro-robots. Several other micro-robots with special driving methods are then introduced. Finally, the current problems of crawling micro-robots are presented, and the future development direction is prospected.

2 Quadruped Crawling micro-Robots

Quadruped bionic micro-robots have mainly been inspired by the gaits of land mammals, reptiles, and quadrupedal creatures. Quadruped robots have good movement flexibility and excellent environmental adaptability, and are a research hotspot in the field of walking robots. In recent years, the development of high-performance quadruped robots with high dynamics, high adaptability, high stability, and high load capacity has become the mainstream research direction in the field of bionic robot technology.

2.1 Harvard Ambulatory Micro-Robot (HAMR)

The Wyss Institute for Biologically Inspired Engineering at Harvard University took inspiration from cockroaches and produced the Harvard Ambulatory Micro-Robot (HAMR) (shown in Fig. 1). Due to their passive and stable body shape, these robots can run on many complex terrains at high speed. At present, these robots already exist independently of an external power supply, [19] and can jump, turn, [20] sink, [21] climb, [22] and even move on the surface of an object via adhesion [23, 24]. HAMR has undergone more than ten years of iterative upgrades, from the first generation of HAMR-I in 2008 [25] to HAMR-II·[26] HAMR-III [27], HAMR-IV, HAMR-V [28], and HAMR-VI [29]. The latest HAMR-VI robot is based on the previous HAMR platform [30, 31]; it is a micro-robot with a length of 4.51 cm and a weight of 1.43 g, and has eight independently actuated degrees of freedom (DOFs). The robot can use multiple closed-loop gaits to achieve high-speed horizontal ground motion [32]. In addition, as depicted in Fig. 2a, the research team also developed HAMR-JR, which has the same structure as HAMR-VI, in 2020. While it has a smaller size (length 2.25 cm, weight 0.32 g), it has the same motion ability as HAMR-VI [33]. The schematic diagram of the leg structure of HAMR-VI is shown in Fig. 2b. It is constructed by the micro-electro-mechanical system (MEMS) process, and each leg is composed of two piezoelectric actuators (Fig. 2c).

Piezoelectric ceramics can be used as micro-drives in some micro-devices due to their shape-changing characteristic when subjected to voltage. HAMR is a typical representative of the use of piezoelectric ceramics. The piezoelectric actuator of HAMR (shown in Fig. 2c) uses lead zirconate titanate (PZT) piezoelectric ceramics as the piezoelectric material, which has a good piezoelectric effect. When driving the piezoelectric actuator, HAMR uses a synchronous driving method to provide a constant high voltage bias on the external driver board, and to provide a drive signal to the center electrode. With the efforts of the members of the Wyss laboratory, continuous breakthroughs have been made in the manufacturing process of piezoelectric actuators [34–36]. At present, the yield and repeatability of piezoelectric actuators have been significantly improved, and multiple piezoelectric actuators can be manufactured simultaneously to meet the requirements of HAMR.

When moving, the lift and swing piezoelectric actuators swing due to the passage of electric current. The lift piezoelectric actuator swings to drive the lift input and spherical five-bar movement, which moves the mechanical framework up and down. The swing of the swing piezoelectric actuator drives the swing input and spherical five-bar movement, which moves the mechanical framework forward and backward. By controlling the magnitude and direction of the current, the swing direction of the piezoelectric actuator can be controlled, thereby completing a movement cycle of a leg (shown in Fig. 2b).

2.2 Miniature Independently Actuated-Legged Quadruped (MinIAQ)

Researchers at Bilkent University developed the origami micro-robot Miniature Independently Actuated-legged Quadruped (MinIAQ) [37]. MinIAQ-I, as shown in Fig. 3a, is a quadruped robot weighing about 23 g and made of a single A4-size sheet of polyester (PET) film. It can run for about 30 min under the support of a fully charged 150-mAh single-cell lithium polymer (LiPo) battery. MinIAQ-II [38, 39], as depicted in Fig. 3b, is an improvement of MinIAQ-I characterized by the optimization of the leg structure. It is 12 × 6 × 4.5 cm in size and 23 g in weight. Compared with MinIAQ-I, its speed is increased from 0.65 body length/sec to 0.8 body length/sec. Moreover, MinIAQ-II has a better leg mechanism, a longer stride, better traction, and less joint bending flexibility, thereby allowing it to achieve faster and more stable

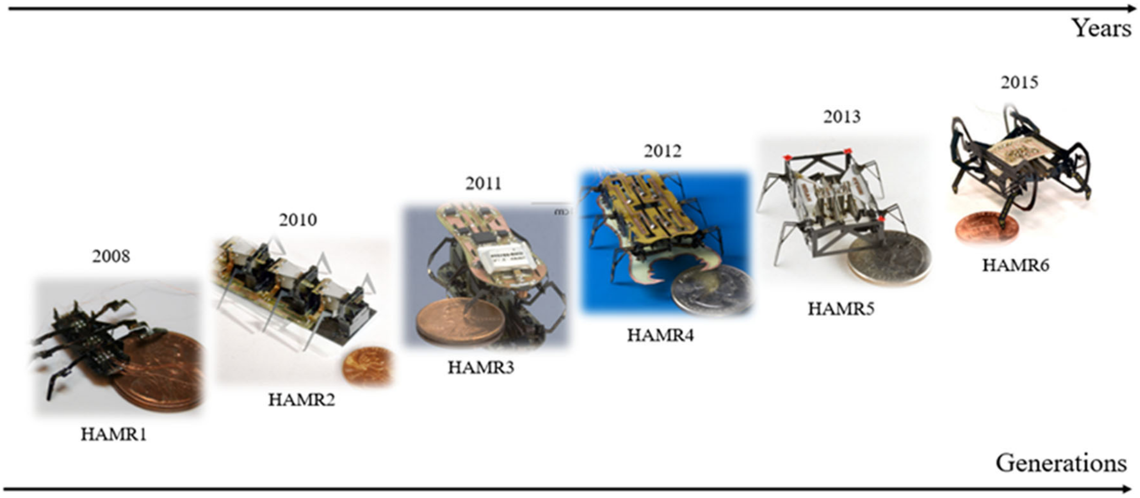


Fig. 1 The HAMR series

walking, better maneuverability, and longer durability and joint life. Although MinIAQ-II was designed as a quadruped micro-robot, it can be modified to an *n*-foot micro-robot if these *n* individually driven legs are connected.

As a traditional micro-robot driving tool, micromotors play a pivotal role in the field of micro-robot driving. Because it can load micromotors, MinIAQ adopts a motor-driven method; it.

is driven by four independent micromotors whose connectors are connected to the center of a disk, and the holes on the periphery of the micro-disk are bridged with the legs of the micro-robot (shown in Figs. 3c-d). When the micromotor is

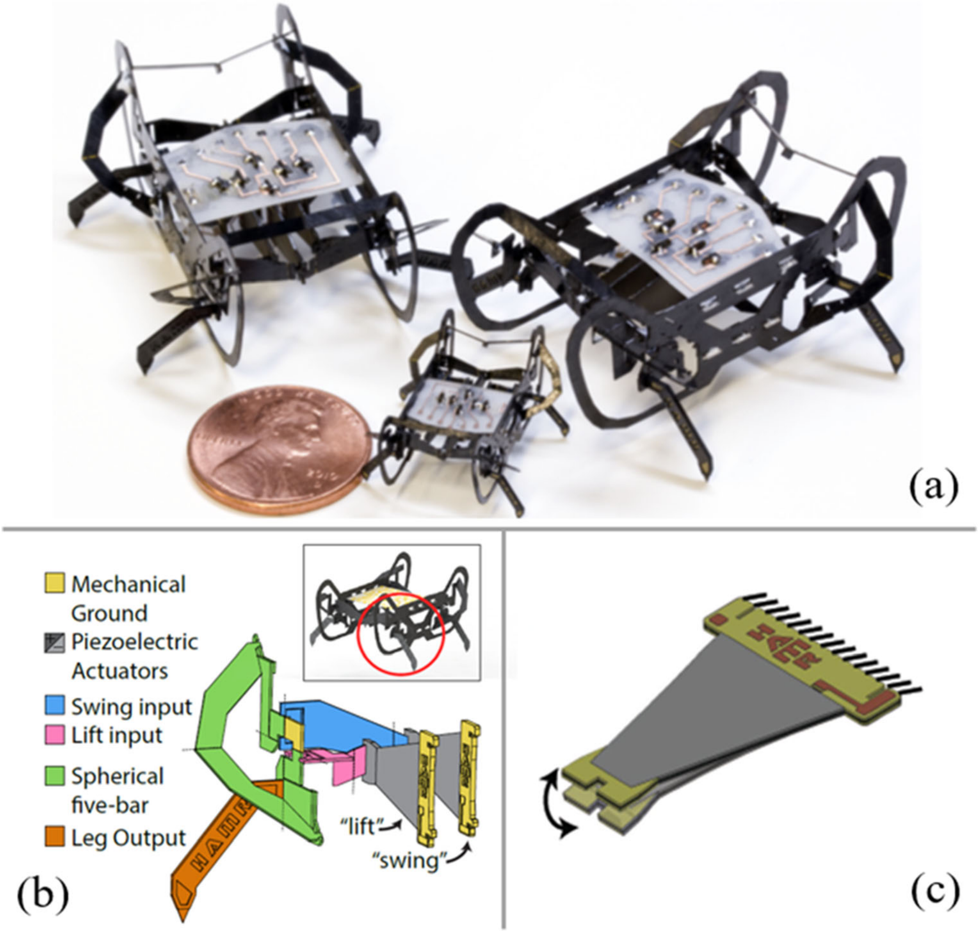
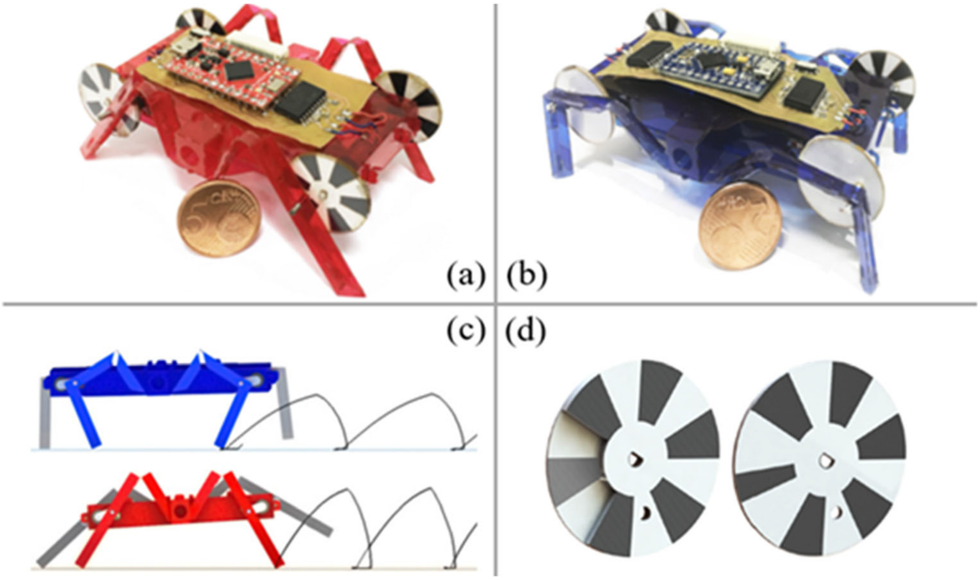


Fig. 2 HAMR-JR and its drive structure [33]: (**a**) HAMR-VI and HAMR-JR size comparison; (**b**) the leg drive structure of HAMR-JR; (**c**) the piezoelectric actuator of HAMR-JR.

Fig. 3 MinIAQ and its drive structure [37, 38]: (**a**) MinIAQ-I; (**b**) MinIAQ-II; (**c**) leg movement trajectories of MinIAQ-I and MinIAQ-II; (**d**) drive discs of MinIAQ-I and MinIAQ-II



subjected to various types of rotation by the current, the disc also rotates and drives the micro-robot to move.

2.3 Nihon University's MEMS micro-Robot

The research team of Nihon University has developed several micro-robots by imitating the gait of insects [40–44] (shown in Figs. 4a-c), among which the millimeter-level quadruped MEMS micro-robot depicted in Fig. 4a is the most representative [42]. The robot is 7.2 × 4.6 × 6.4 mm in size. Moreover, it uses an artificial muscle wire constructed of a shape-memory alloy (SMA) as an actuator, which can easily achieve miniaturization and a light weight. The SMA driver has the advantages of a simple structure, light weight, no noise, and no pollution, and can be controlled by controlling the voltage and power-on time [45]. The actuator does not require a complicated mechanism, and the artificial muscle line is stretched and relaxed by the electric current flowing through it. As illustrated in Fig. 4d, Nihon University's MEMS micro-robot uses NiTi alloy to make artificial muscle

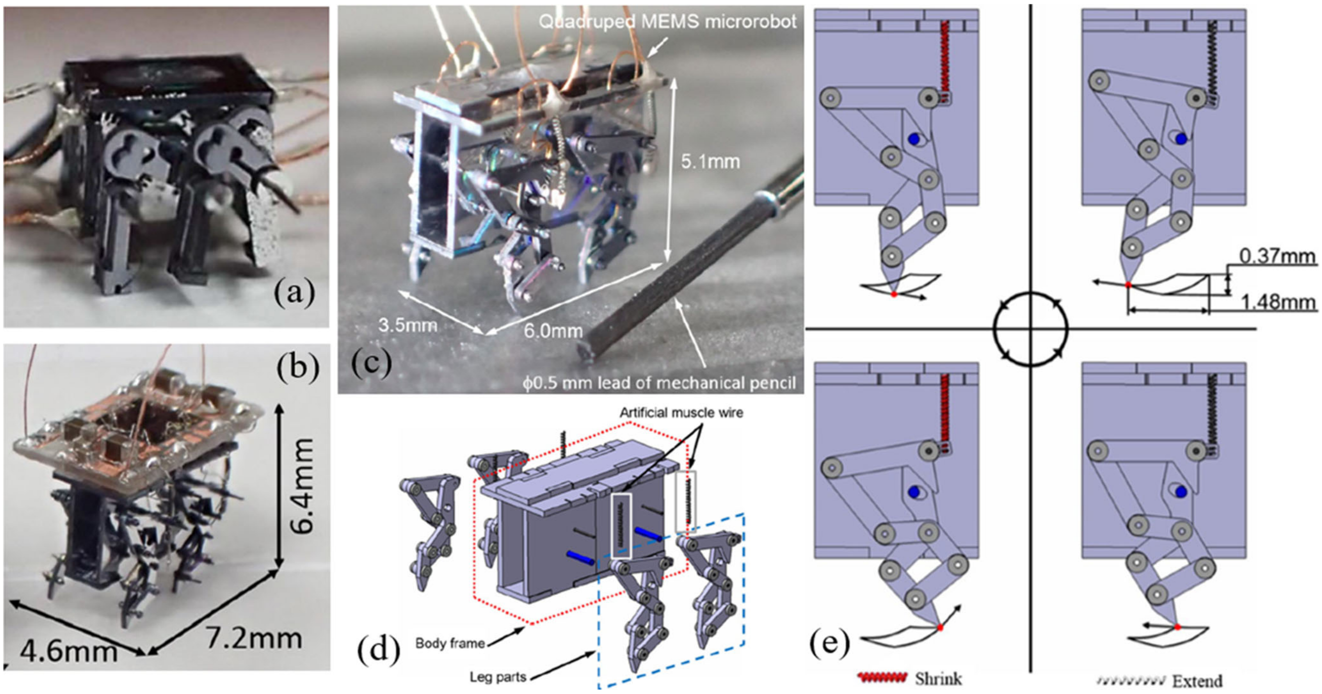


Fig. 4 Nihon University MEMS micro-robot: (**a**) the MEMS micro-robot structure [44]; (**b**) the MEMS micro-robot with an on-board circuit [42]; (**c**) the MEMS micro-robot without an on-board circuit [40]; (**d**) the structural diagram of the MEMS micro-robot [40]; (**e**) the leg movement diagram of the MEMS micro-robot [40]

lines to drive the micro-robot. This alloy is characterized by high strength, high plasticity, corrosion resistance, and low cost, and is the most widely used. The copper wire connecting the external controller and the artificial muscle wire is connected with conductive paste to ensure that the current can be smoothly conducted to the artificial muscle wire with a small loss [40].

Fig. 4e presents an example of the linkage mechanism and the movement of the legs. The combination of two groups of four-bar linkages produces the walking motion of the legs. When the artificial muscle line is contracted, the leg moves backward; in the case of artificial muscle line extension, the leg moves forward. The linear motion of the contraction and extension of the artificial muscle line is transformed into the pedal-type swing motion of the leg. The trajectory shows that the leg can move in the air after kicking the ground. The movement of the quadruped robot is realized by only four artificial muscle lines.

2.4 C-Quad and S-Quad

C-Quad (shown in Fig. 5b) and S-Quad (shown in Fig. 5a) [46, 47] are two quadruped micro-robots developed by Bilkent University researchers in 2017 and 2020, respectively. C-Quad is an origami-inspired, foldable, miniature robot whose legs and body are all machined from one PET sheet each. C-Quad comprises a battery, an Arduino Pro Micro control board, a Bluetooth communication module, and custom encoder and other modules, and its total weight is 38 g. By using a very simple control strategy, it can reach a speed of 2.7 body length/sec. It can also perform in-place turns and climb over obstacles more than half of its height.

S-Quad is a novel miniature soft-legged robot with a flexible printed circuit board (PCB). Researchers designed and manufactured a special C-shaped leg for S-Quad, which is constructed of polydimethylsiloxane (PDMS) soft material. Although its speed is not as fast as that of C-Quad, it can climb over obstacles 1.44 times its height, and is therefore expected to play a role in some unique situations in the future.

2.5 Quadruped micro-Robot Comparison

It can be seen from Table 1 that among the quadruped micro-robots, HAMR-VI developed by the Wyss Institute of Biological Inspiration at Harvard University has the fastest speed, and HAMR-JR has the best body length/speed ratio; these factors are determined by the unique spherical four-bar linkage motion structures of these micro-robots. The spherical four-bar linkage structure can effectively convert the vibration of the piezoelectric actuator into leg motion. The superiority of the motion structure has laid a good foundation for the further development of micro-robot technology. Several micro-robots developed by Bilkent University, such as MinIAQ-I, MinIAQ-II, C-Quad, and S-Quad, are driven by motors. Among them, MinIAQ-I, MinIAQ-II, and C-Quad are all origami miniature robots, while S-Quad is a soft robot. Due to the unique design of its leg structure, C-Quad is the fastest of these miniature robots, and is capable of running at a speed of 27.81 cm/s. As a unique soft micro-robot, S-Quad can climb over obstacles 1.44 times higher than its own height. This is because it uses a flexible PCB and PDMS flexible materials. Soft-legged robots are also a good direction for exploration. Nihon University's MEMS micro-robot is currently the lightest and smallest four-legged micro-robot. While its motion ability is worse than that of the previously introduced micro-robots, as the only quadruped micro-robot in this review that uses an SMA as the actuator, it indicates the direction for the further miniaturization of micro-robots in the future.

As presented in Table 1, SMAs are small and can be made into micro-robots with miniature dimensions (less than 1 cm in length). However, the poor linear deformability (about 8%) of SMAs also results in a great reduction in the maneuverability of micro-robots. Due to their size limitations, micromotors can only drive some larger micro-robots (>5 cm), but they have advantages including a low cost and a simpler mechanical structure design. As a new driving device developed in recent years, the performance of piezoelectric ceramics is between those of micromotors and SMAs. Compared with those

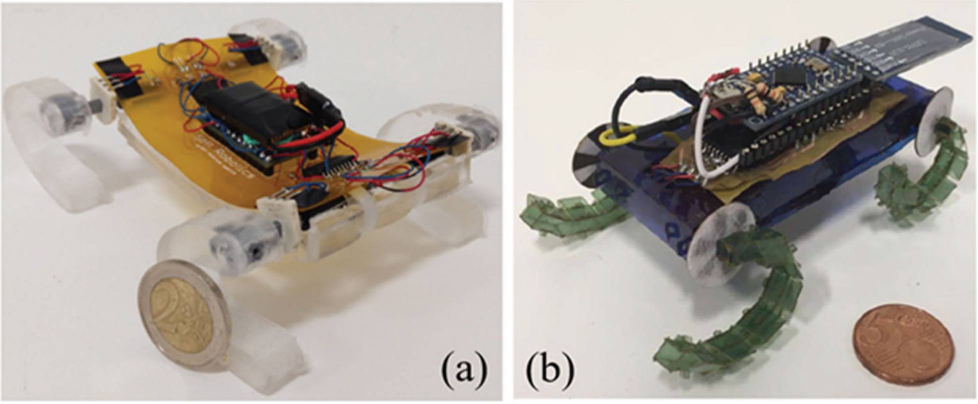


Fig. 5 The S-Quad and C-Quad micro-robots: (**a**) S-Quad [47]; (**b**) C-Quad [46]

Table 1 The comparison of various quadruped micro-robots

Year	Micro-robot	Mass (g)	Length (cm)	Velocity (cm/s)	BL/s	Actuator	Highlights
2008	HAMR-1	0.09	1.7	0.1	0.06	Piezoelectric ceramics	First Harvard ambulatory micro-robot prototype
2011	HAMR-3	1.7	4.7	4.3	0.91	Piezoelectric ceramics	HAMR’s first version with an onboard control circuit and battery
2015	HAMR-VI	1.41	4.51	47.8	10.60	Piezoelectric ceramics	The fastest version of HAMR, based on which many other applications have been expanded
2017	MinIAQ-I	23	12	7.8	0.65	Micromotor	The micro-robot is very light (Compared to its size)
2017	MinIAQ-II	23	12	9.6	0.8	Micromotor	The leg mechanism has been optimized to achieve faster speed. (Compared to MinIAQ-I)
2017	C-Quad	38	10.3	27.81	2.7	Micromotor	The micro-robot can complete difficult motion tasks, such as turning with a zero radius
2018	MEMS micro-robot (onboard circuit version)	0.096	0.72	0.41	0.57	Shape-memory alloy	The smallest micro-robot on this list, also characterized by good movement ability
2020	S-Quad	69	15	8.1	0.54	Micromotor	The miniature robot can climb over obstacles 1.44 times its own height
2020	HAMR-JR	0.32	2.25	31.3	13.91	Piezoelectric ceramics	The advanced version of HAMR-VI, which is smaller and lighter and has a fast speed

driven by SMAs, micro-robots driven by piezoelectric ceramics are larger in size but more maneuverable. Moreover, compared with those driven by micromotors, micro-robots driven by piezoelectric ceramics are smaller in size but do not have the advantages of the easy fabrication and lower cost of micromotors.

3 Hexapod Crawling micro-Robots

Hexapod bionic micro-robots mainly imitate hexapod insects and arthropods. Hexapod robots have high flexibility and strong environmental adaptability while causing little damage to the ground, and their redundant structure also ensures stable walking even when one leg loses the ability to move.

3.1 Robotic, Autonomous, Crawling Hexapod (RoACH) micro-Robot

Since 2008, researchers at the University of California, Berkeley, have been working on the RoACH (Robotic, Autonomous, Crawling Hexapod) series of micro-robots. The earliest RoACH is a hexapod robot with a size of 3 × 2.5 × 1.5 cm, and its weight is 2.4 g (shown in Fig. 6) [48]. The skeleton of RoACH is manufactured using the smart composite material microstructure (SCM) process. RoACH is driven by SMAs, which are thermal actuators that require a voltage of 13.6 V and a current of 60 mA to drive them. RoACH has a 20-mAh LiPo battery that weighs 847 mg, which allows it to run continuously for 9 min at a frequency of 3 Hz.

Researchers have developed several larger crawling micro-robots based on RoACH, including DynaRoACH, OctoRoACH, VelociRoACH, and LoadRoACH, as respectively depicted in Fig. 6 [48–52]. These micro-robots are all driven by micromotors, so they have better maneuverability. For example, DynaRoACH [49] is 10 cm long and weighs about 24 g, and can run at a speed of 1.4 m/s at 20 Hz. VelociRoACH [51] has a body length of about 7.5 cm, a height of 4.5 cm, and a weight of 53.6 g. It is powered by a 300-mAh LiPo battery. Thus far, VelociRoACH is the fastest of the RoACH-derivative series of miniature robots. OctoRoACH [50] is an eight-legged miniature robot that is 13 cm long and weighs about 35 g. The robot is driven by two motors and can run at a speed of 0.5 m/s at 25 Hz. Although its speed is not as fast as that of VelociRoACH, because of its eight-legged and dual-motor-driven design, the robot can turn at a speed of about 400° per second, which is far better than the turning ability of the single-motor-driven VelociRoACH. LoadRoACH [52] is a 55 g palm-sized robot that can dynamically operate while carrying a payload equivalent to 50% of its body weight. LoadRoACH has a small tail structure that can make the micro-robot turn by hitting the ground. In addition, researchers at the University of California, Berkeley, have conducted a series of interesting explorations based on these robots, such as tumbling, jumping, etc., which has further broadened the scope of their application. In addition, researchers at the University of California, Berkeley, have also developed many outstanding RoACH-derived micro-robots [53–57], and these micro-robots are therefore more likely to be used in real environments.

DynaRoACH [49], OctoRoACH [50], VelociRoACH [51], and LoadRoACH [52] are all driven by motors.

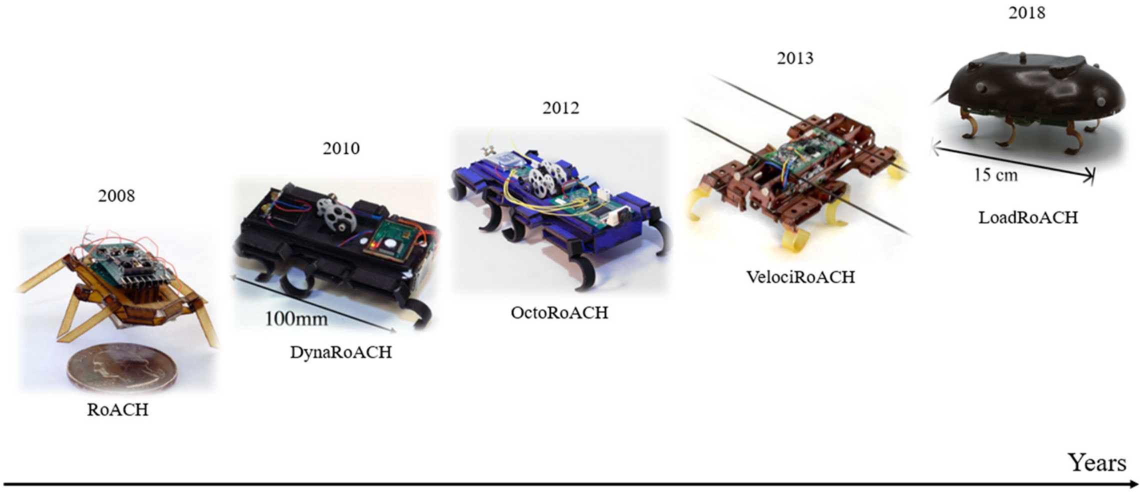


Fig. 6 The RoACH series of micro-robots

Among them, DynaRoACH, VelociRoACH, and LoadRoACH [52] are hexapod micro-robots driven by a single motor, but OctoRoACH is an eight-legged micro-robot driven by dual motors. Taking DynaRoACH as an example, the kinematic structure of the hexapod micro-robot consists of two original single-DOF structures, namely a slider-crank connecting rod structure and a parallel four-bar linkage structure. The four-bar linkage uses simple parallel geometry, so the transmission ratio is 1. The rear and side views of the ideal kinematics of the robot are respectively illustrated in Fig. 7a and b, from which it can be seen that the coupler is driven by the output of the motor, and the output of the four-bar linkage is taken from the crank connecting rod. The slider-crank connecting rod structure can realize the retraction and retraction of the legs, while the four-bar connecting rod structure can carry out the forward and retreating motion of the legs.

3.2 Dynamic Autonomous Sprawled Hexapod (DASH) micro-Robot

The Dynamic Autonomous Sprawled Hexapod (DASH) micro-robot, as depicted in Fig. 8a, was also developed by the University of California, Berkeley. This small, light, and powerful micro-robot is 10 cm long and weighs 16.2 g [58]. The DASH micro-robot is manufactured by the SCM process via the use of a single DC motor, a differential drive structure, and a small SMA to drive it, and can run at a speed of up to 1.5 m/s at a frequency of 17 Hz. SCM technology is used for the DASH micro-robot to create an integrated structure and external components from lightweight materials without the use of fasteners, which improves its robustness; DASH can be dropped from a height of 10 m without damage. The steering performance of DASH is also excellent, namely up to 50° per second when turning left, and up to 55° per second when turning right (the difference between turning to the left and right is due to the difference in the triangular gait between the left and right sides). The research team even added gliding wings to DASH [59] so that the micro-robot can float briefly after reaching a certain speed and height.

The driving method of DASH is completely different from that of the RoACH series of robots. DASH uses rigid links and polymer hinge elements to transmit power from the motor to the legs, and the mechanism is like a paddle. When the input trajectory is circular, the end of the leg follows a similar circular output trajectory. In DASH, the movement of the motor is transmitted through the paddle structure to drive the leg to make a circular motion. The vertical and back-and-forth movements of the legs of DASH can be described separately. The kinematics model of the joints is presented in Fig. 8. The front view (Fig. 8b) shows the vertical movement of the legs, with a pair of legs moving vertically in opposite directions. The top view (Fig. 8c) shows the horizontal movement of the legs, with the four-bar linkage mechanism swinging one leg forward and the other leg swinging backward. These two motions are then coupled together so that the circular output of the DC motor drives both the vertical and horizontal displacement of the model. The DASH design has three pairs of two-legged structures to achieve an alternate three-legged gait.

3.3 Miniature Resonant Ambulatory Robot (MinRAR)

Researchers at the University of Newcastle in the United Kingdom began to develop a monolithic piezoelectric micro-robot in 2016. The first generation of piezoelectric robots (shown in Fig. 9a) was very small [60] and when driven at 350 Hz, the robot could achieve a walking speed of up to 350 mm/s. In the same year, the team developed a miniature robot called the Miniature Resonant Ambulatory Robot (MinRAR V1) [61] (shown in Fig. 9b). MinRAR V1 is 55 mm in length and 16 g in weight. It is powered by a piezoelectric bimorph bender and has a maximum speed of 520 mm/s. Each leg of the micro-robot consists of two

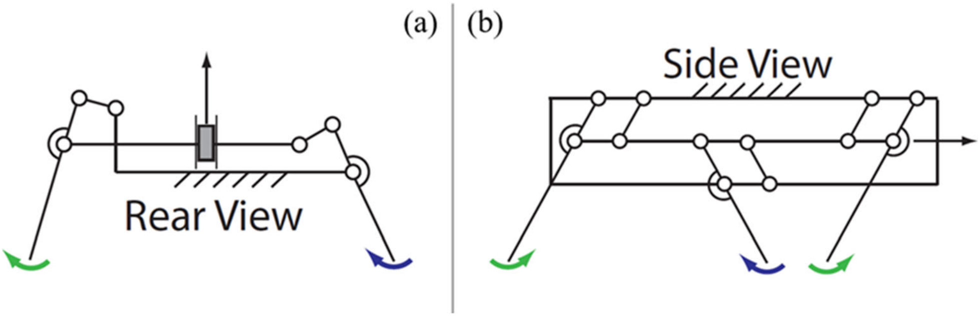


Fig. 7 The leg linkage structural movement diagram of DynaRoACH [49]: (**a**) the rear view of the ideal kinematics; (**b**) the side view of the ideal kinematics

bimorph benders installed side by side, which are connected to the end actuator at the tip via bending. The main part of the micro-robot is printed using 3D printing technology. While this technology can quickly produce the required shape, its minimum feature size is limited to 0.5 mm, which makes it difficult to load some additional sensors onto the micro-robot. In addition, as shown in Fig. 9c, the researchers also designed an upgraded version of MinRAR V2 in 2017 [62], which has onboard electronic devices and an external LiPo battery that can provide a voltage of 3.7 V. When driven at a frequency of 190 Hz, the maximum speed of MinRAR V2 is 98 mm/s, and when driven at 5 Hz, the speed can reach 6 mm/s. Due to the addition of control equipment and batteries, the weight of the micro-robot is correspondingly increased to 28 g, which is almost twice that of MinRAR V1; thus, its speed is relatively slow as compared to that of MinRAR V1.

The MinRAR micro-robot is driven by a piezoelectric actuator made of piezoelectric ceramics. The tip of the bimorph is connected by an aluminum end effector, and the end is composed of a bent part and a leg, as shown in Fig. 9d. Unlike the leg structures of most other micro-robots, the piezoelectric actuator of this micro-robot is integrated into the mechanical structure. The curved piezoelectric sheet is driven by a biased bipolar electrical structure, which uses the superposition of positive and negative electric fields to achieve the maximum deflection force. By driving each curved piezoelectric sheet with a sinusoidal waveform and changing the phase between the two sheets, various motion paths can be realized at the end actuator. Most importantly, when the two piezoelectric plates are driven completely out of phase, a circular motion can be generated at the end of the end actuator.

3.4 Soft Modular Legged Robot (SMoLBot)

The Soft Modular Legged Robot (SMoLBot) [63] is a miniature, foldable, modular, and soft hybrid legged robot developed by researchers at the University of California, Berkeley, in 2020 (as shown in Fig. 10a). The body and movement mechanism of SMoLBot are folded from acetate fiberboard, and the connection mechanism is molded from PDMS. Each module in SMoLBot has a width of 44.5 mm, a length of 16.75 mm, and a height of 15 mm. Each module is driven and controlled by two independent DC motors. If the high-rigidity moving parts are connected with the compliant parts, the micro-robot can achieve high mobility and a stable walking mode. SMoLBot-C [64] is a micro-robot with soft C-shaped legs (shown in Fig. 10b), and was evolved on the basis of SMoLBot. As compared with a C-legged robot with rigid legs and spine, a C-legged robot with soft legs and a soft spine can climb higher obstacles and walk on surfaces with a larger tilt angle.

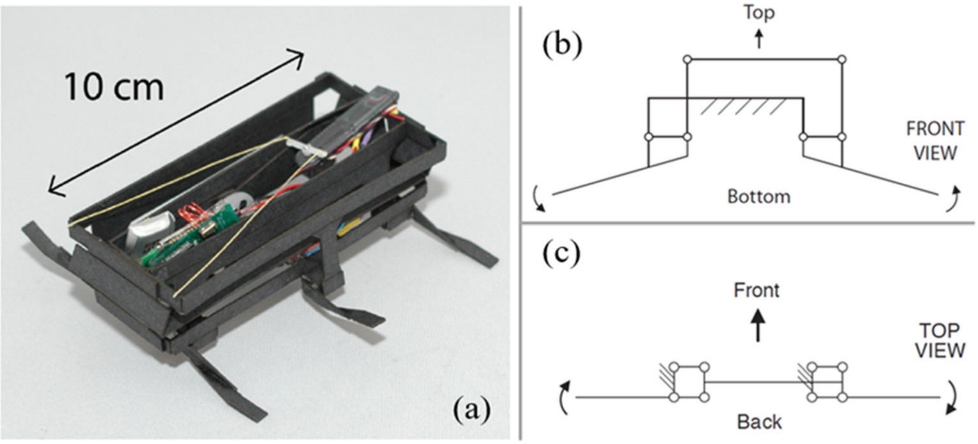


Fig. 8 DASH and its motion link diagram [58]: (**a**) the front view of the ideal kinematics; (**b**) the top view of the ideal kinematics

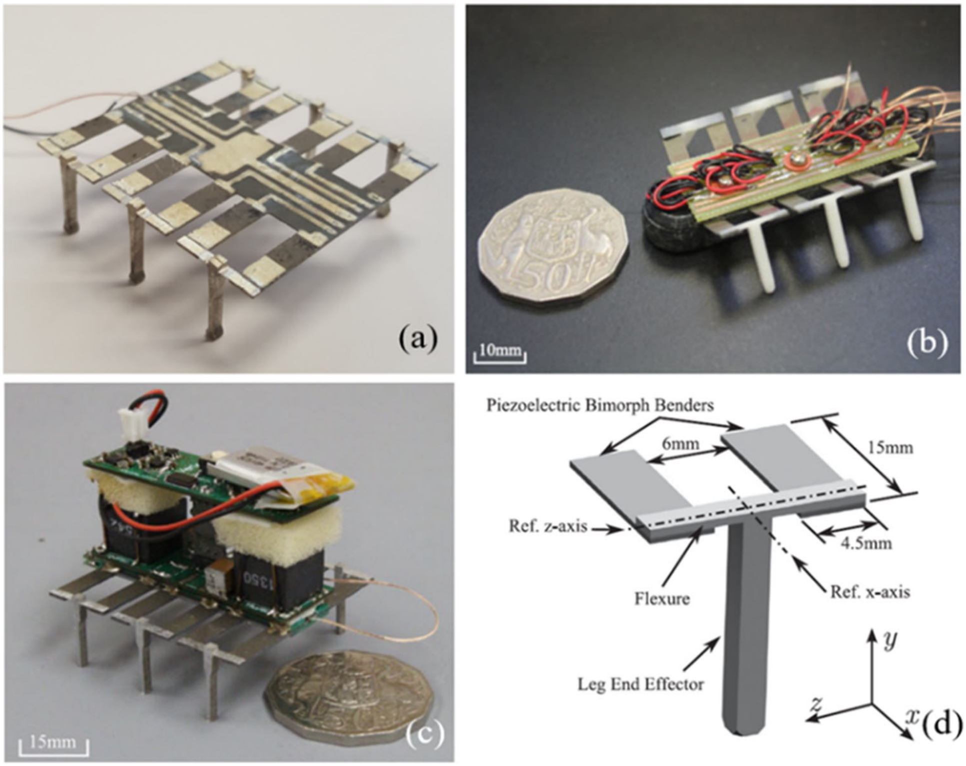


Fig. 9 The MinRAR micro-robot: (**a**) the first generation of piezoelectric robots [60]; (**b**) the MinRAR V1 micro-robot [61]; (**c**) the MinRAR V2 micro-robot [62]; (d) the piezoelectric actuator model of MinRAR V1 [61]

3.5 Hexapod micro-Robot Comparison

As reported in Table 2, VelociRoACH is the fastest of these hexapod micro-robots, and, in fact, is also the fastest micro-robot reviewed in this article. The VelociRoACH driven by a micromotor has a body length of only 10 cm, but it can run at a speed of 270 cm/s, which is a very good result. The speed of DASH (body length of 10 cm) has also reached an astonishing 150 cm/s, and its weight is only 16.2 g, which is already outstanding for a motor-driven micro-robot. In addition, as the oldest micro-robot reviewed in this section (the only one that uses an SMA), RoACH was the first micro-robot developed using SCM technology. Regarding LoadRoACH, which is also a RoACH-derived micro-robot, although its speed is not as exaggerated (72 cm/s) as that of its predecessor (VelociRoACH), it has excellent steering capabilities. The MinRAR series of micro-robots use piezoelectric materials as the driver. When the power supply and circuit board are not onboard (MinRAR V1), the speed can reach 52 cm/s, but when they are onboard (MinRAR V2), the speed is only 9.8 cm/s; thus, this is a direction that requires further optimization in the future.

It is evident from Table 2 that SMAs are suitable for small-scale micro-robots, piezoelectric ceramics are suitable for medium-scale micro-robots, and micromotors are suitable for larger-scale micro-robots. VelociRoACH and DASH are significantly faster than the other hexapod micro-robots; this is because micromotors can often run at higher frequencies, so the micro-robots that adopt micromotors have a faster pace frequency. Micro-robots driven by piezoelectric ceramics are slower, and those driven by SMAs are the slowest. On the one hand, the size of the micro-robots driven by these two driving methods is relatively small. On the other hand, because the received power is different, the voltage driven by the SMA and the piezoelectric ceramic is smaller, as is the generated power.

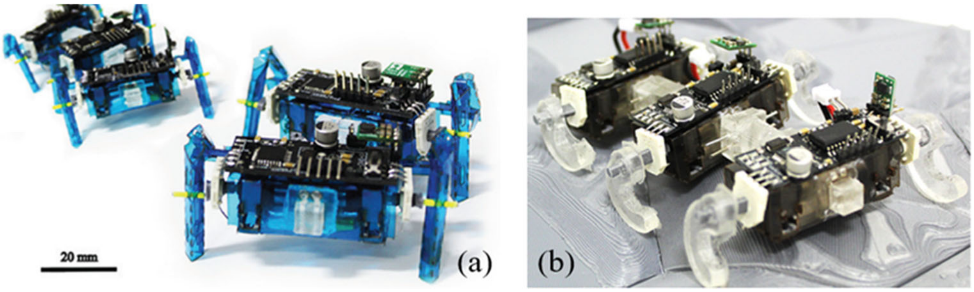


Fig. 10 SMoLBot micro-robots: (**a**) SMoLBot [63]; (**b**) SMoLBot-C [64]

Table 2 The comparison of various hexapod micro-robots

Year	Micro-robot	Mass (g)	Length (cm)	Velocity (cm/s)	BL/s	Actuator	Highlights
2008	RoACH	2.4	3	3	1	Shape-memory alloy	The first micro-robot made using SCM technology
2009	DASH	16.2	10	150	15	Micromotor	Excellent athletic ability relative to its age
2013	VelociRoACH	30	10	270	27	Micromotor	The fastest legged robot built to date, relative to its scale
2017	MinRAR V1	16	5.5	52	9.45	Piezoelectric ceramics	Under the action of resonance vibration, a good movement speed can be achieved
2018	MinRAR V2	28	5.5	9.8	1.78	Piezoelectric ceramics	An onboard drive circuit and battery (compared to MinRAR V1)
2018	LoadRoACH	55	15	72	4.8	Micromotor	The micro-robot has excellent steering ability and can run in some extreme environments
2020	SMoLBot	54	48	64.26	1.34	Micromotor	A modular design; it can be made into four-legged, six-legged, and other-legged micro-robots
2021	SMoLBot–C	50.25	36	<40	<1.11	Micromotor	This robot with soft legs and a soft spine has the highest velocity among the other hexapod robots

4 Discussion

4.1 Other Emerging micro Crawling Robots

The quadruped and hexapod micro crawling robots mentioned above have excellent motion strategies and drive design and are common in the field of micro-robots. However, many other excellent bionic micro crawling robots have also emerged in recent years.

4.1.1 3D Printed micro Crawling Robot

The vigorous development of 3D printing technology has facilitated the development of some micro-robots that cannot be produced by conventional processing methods [65, 66]. For example, researchers from the University of Utah and the University of Nevada produced a 3D printed micro-robot ionic polymer-metal composite (IPMC) soft crawling micro-robot in 2017 [65]. IPMC is an artificial muscle material that will bend in different directions when voltages are applied to its two sides. It is highly suitable as a new type of actuator for biomimetic robots due to its characteristics of large displacement and deformation under lower driving voltage [67–70].

Micro-robot design takes inspiration from the anatomy of a caterpillar with a modular body structure (as shown in Fig. 11a) that includes body units and leg units (as shown in Fig. 11b). The body unit is an elliptical actuator that extends when a voltage is applied, where the outside is the anode, and the inside is the cathode. The body part contracts when a reverse voltage is applied to these electrode pairs. The leg unit is a circular-like structure and is attached to the body part through a coupling mechanism. The legs open when a forward voltage is applied to these electrode pairs and close when a voltage is applied in the reverse direction (Fig. 11b). The micro-robot can move forward in a peristaltic manner through the cooperation of the body and leg units and has a speed of 1.55 cm/s in the optimal mode.

4.1.2 Magnetically Driven micro-Robot

Many species in nature, including magnetotactic bacteria, some birds, and butterflies, rely on the magnetic field to determine their position and adjust their movement direction [71]. Inspired by these species, scientists have employed the same principle to study magnetically driven micro-robots. As an emerging micro-robot drive method, the magnetic drive does not require the design of special moving parts because its driving force is directly derived from the force of the magnetic field, meaning attention can be focused on enhancing the functions of the micro-robot. Many outstanding works have appeared in the field of magnetically driven micro-robots [72–76]. These micro-nano robots are capable of specialized functions, including diagnosing diseases and improving the environment.

Researchers discusses the manufacture and control of a nickel-plated magnetic micro-robot [73] whose main body is a $35*30*3\mu m^3$ U-shaped piece (as shown in Fig. 12a). The micro-robot manufacturing process includes two steps: lithography and magnetization. The first step employs standard photolithography to construct the SU-8 photoresist body of the micro-robot. In the second step, a nickel film is plated on the SU-8 body and then magnetized (as shown in Fig. 12a). The SEM image of the finished micro-robot is provided in Fig. 12b. A two-dimensional magnetic field control system consisting of four electromagnetic coils is then constructed to control the magnetic micro-robot (as shown in Fig. 12c). These electromagnetic coils form the magnetic field that

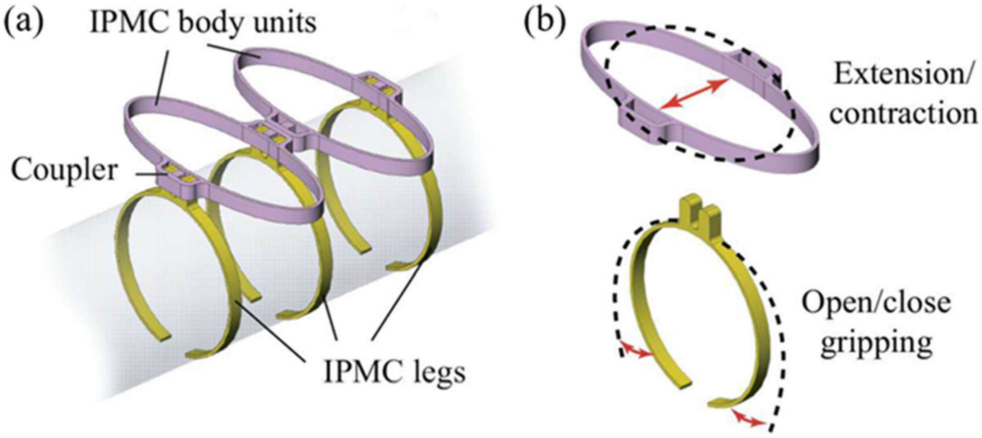


Fig. 11 3D printed micro-robot [65]: (**a**) the micro-robot composition; (**b**) the Schematic diagram of the movement of the body part and the leg part of the micro-robot

drives the nickel-plated micro-robot, where the direction of the magnetic field is changed by switching the direction of the current in the coil. Two relays are used to switch the direction of the magnetic field, which is controlled by computer programming (as shown in Fig. 12d). The micro-robot can be driven manually through the computer or programmed to realize movement toward a target object.

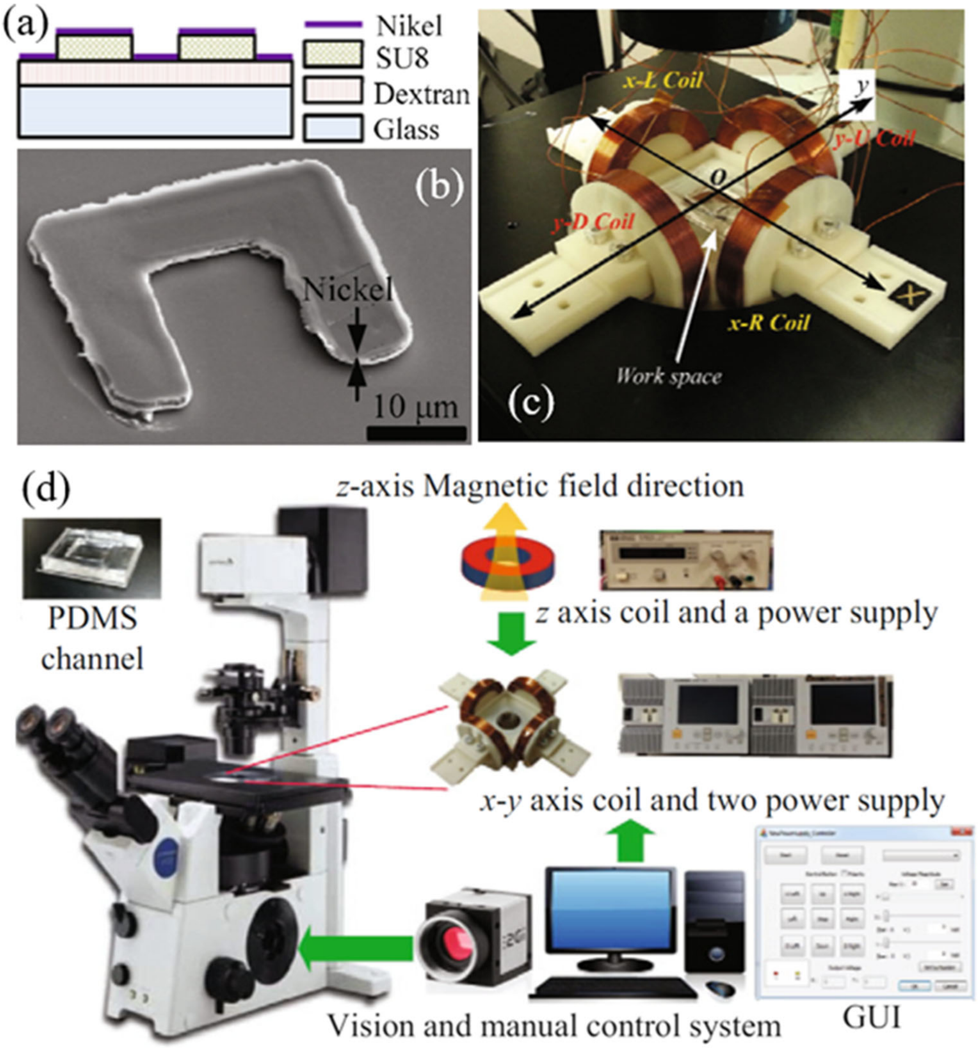


Fig. 12 Magnetically driven micro-robot [73]: (**a**) the micro-robot composition; (**b**) the micro-robot SEM image; (**c**) the Magnetic drive device for micro-robot; (**d**) the Control equipment of micro-robot

4.1.3 Light-Driven micro-Robot

Light is a universal energy source, and its various characteristics, such as wavelength and intensity, can be optimized for specific needs [77]. Light-responsive liquid crystal polymer technology has developed rapidly in recent years and has been proven to be an effective actuator for micro-robots. Appropriate liquid crystal polymers can change shape when irradiated by light and then return to their original shape when the irradiation is stopped. Many light-driven micro-robots employing these technologies have emerged [78–82], combining micro-robot technology and light-driven materials.

Researchers proposes a light-driven micro-robot [80], which is a centimeter-level strip-shaped robot structure that can perform a variety of motions on human hair. The micro-robot is made of a light-responsive liquid crystal network (LCN) (Fig. 13a), an inherently thermoresponsive artificial muscle whose macroscopic deformation is triggered photothermally [83]. Figure 13b shows that the micro-robot has a larger curvature when there is no light, and the curvature decreases when there is light. By proper modulation of the light, the micro-robot can achieve directional crawling and even vertical climbing on hair strands [80].

4.2 Existing Problems

While micro-crawling robot technology has been optimized significantly, many factors continue to limit further development of the technology.

4.2.1 Materials

Material science is vital to the process of micro-crawling robot manufacturing. The torso and actuators of micro-robots require different types of materials. The current development of micro crawling robots with high motion performance has encountered a bottleneck in the centimeter order of magnitude, where further reduction in size will inevitably lead to a substantial decline in motion capabilities. More powerful actuators are needed to overcome this bottleneck, and the development of drive technology depends on material technology. An ideal material for actuator design requires the characteristics of small size, light weight, and high energy density simultaneously. At present, the material closest to these characteristics is SMA, which has been used in some micro-robots, such as the Japanese-developed MEMS micro-robots mentioned in this article. However, these micro-robots do not have effective motion performance (compared to the HAMR and RoACH series of micro-robots) and require more powerful materials to solve these problems.

4.2.2 Actuator

Actuator technology is a key component of micro-robot technology, which directly determines the performance of a micro-robot. At present, mainstream actuators include micromotors, piezoelectric actuators, and shape memory alloy wires. Although there are many excellent micro-robots that employ these three actuators, they still have some shortcomings. Micro-robots driven by micromotors and piezoelectric actuators can achieve extremely high motion performance. Among them, the development of the micromotor is more mature than the piezoelectric actuator, although its volume is larger. A piezoelectric actuator can be made into micro-robots that are smaller than the micromotor. However, a common shortcoming is that they are relatively large, which limits their further development. While the volume of shape memory alloy wire is much smaller than that of micromotors and piezoelectric actuators, micro-robots made with it have reduced motion performance. Recently emerging magnetic drive and optical drive technologies have made the development of micro-nano-level micro-robots possible. However, they have more stringent requirements for adapting to changes in the external environment.

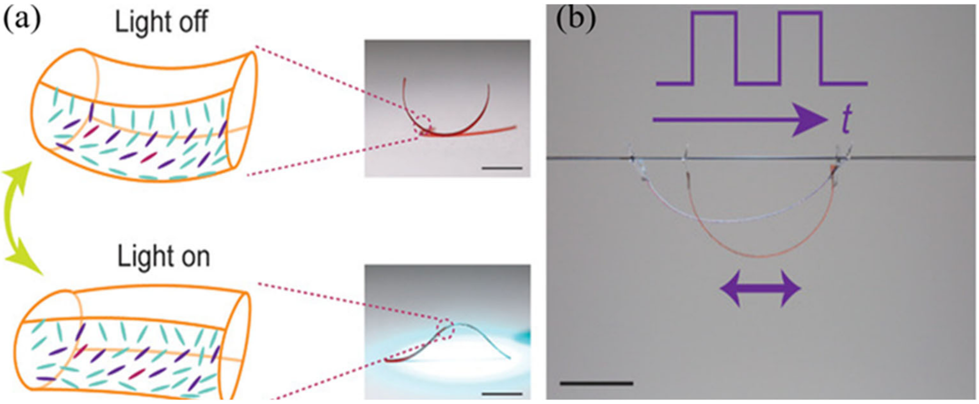


Fig. 13 Light-driven micro-robot [80]: (**a**) the Schematic diagram of the micro-robot bending when illuminated; (**b**) the Curvature changes of micro-robot under illumination

4.2.3 Power Supply

In the design of micro-robots, the power supply strategy is mainly a trade-off between its weight and power control autonomy. For example, in HAMR and MinRAR micro-robots, those with autonomous movement abilities tend to be heavier, which causes a drop in speed. Thus, lighter and smaller power supplies are needed to balance weight and autonomous control capabilities.

4.2.4 Miniaturization and Multi-Function

The most significant feature of micro-robots is their small size, and miniaturization remains a major trend in their continued development. However, due to the recent bottlenecks encountered in the process of further miniaturization of micro-footed crawling robots, many micro-robots with specific functions have appeared [84–86]. These micro-robots have a variety of functions, and their use environment and methods are closer to daily life, so they have better application prospects. How to balance miniaturization and multi-functional capabilities of miniature crawling robots is also a significant challenge for scientists.

4.3 Future Prospects

Crawling micro-robots have important applications in unique working environments, and have consequently attracted the attention of numerous research institutions in recent years. The current crawling micro-robots are mainly quadruped and hexapod robots, and roughly imitate the movements of crawling species in nature. Quadruped and hexapod crawling micro-robots are mostly driven by piezoelectric ceramics, SMAs, and micromotors. Micromotors can often only drive some larger micro-robots, and have the advantages of a low cost and a simpler mechanical structure design. SMAs can be used in some smaller miniature robots, but their mobility will be greatly reduced. The performance of piezoelectric ceramics, as a relatively new type of driving device, is between those of micromotors and SMAs. The development of micro-robots is currently moving in the direction of miniaturization and refinement, but most of the smaller crawling micro-robots require an external power supply and control system, which greatly affects their use scenarios. Although integrated circuit boards and onboard power supplies can be used for some micro-robots, the load capacity will be greatly reduced. Thus, determining how to achieve a compromise between the size and performance of micro-robots is a problem that must be considered by researchers in the future. In addition, when the scale of micro-robots is too small, it would be unrealistic to have a small battery on board. Therefore, researchers must develop a smaller power supply when investigating driving materials to further develop micro-robots in the future.

The current motion capabilities of micro-robots driven by micromotors are adequate but remain limited by the size of the motor itself. As many difficulties remain in the further miniaturization of micromotors, only other characteristics of micro-robots driven by this method can be further developed (such as the LoadRoACH). However, motor-driven micro-robots can load additional modules due to their large size, which also enhances their current application value. Harvard University’s Wyss Institute for Biologically Inspired Engineering has explored a series of special applications for their HAMR micro-robot and achieved good results. However, when the size of the micro-robot is miniaturized to below the centimeter level, an obvious bottleneck appears. The slow deformation of shape memory alloy reduces the speed of micro-robot made with it. Therefore, it is necessary to explore driving materials with better driving efficiency to break through the bottleneck. Moreover, optical and magnetic drive technologies are also experiencing significant development. It is expected that more cross-domain micro-robots will appear in the future, which will promote the further development of micro-robot technology.

5 Conclusion

Micro-robot technology is an important branch of robotics, attracting a large number of researchers worldwide. This article reviewed the development of biomimetic micro crawling robots and analyzed quadruped and hexapod varieties. We first discussed quadruped micro-crawling robots and introduced HAMR, MinIAQ, CQAD, and Nihon University MEMS series micro-robots as four representative quadruped micro-crawling robots. We briefly introduced the basic parameters and development history of these four types of micro-crawling robots, analyzed some popular motion strategies, and finally compared and discussed their parameters. The hexapod micro crawling robot was then discussed, and the RoACH, DASH, MinRAR, and SMoLBot series of micro-robots were selected as representatives, following the same discussion method of the quadruped micro crawling robot. Finally, we introduced several emerging micro-robots with special driving methods and analyzed their driving principles. Some of the remaining problems in the current micro crawling robot technology were detailed, possible solutions were provided, and a future development direction was predicted.

Bionic micro crawling robots have broad application prospects and are expected to have significant value in the future. Although the technology of micro-robots has experienced rapid development in recent years, continued research is required to solve the remaining issues.

Code Availability Not applicable.

Author Contributions Jing Jiang, contributed to the conception of the study. The first draft of the manuscript was written by Mr. Chao Wang and Mr. Hongzu Li. Material preparation, data collection was performed by Mr. Lihao Yang, Mr. Jiale Du, Mr. Peifeng Yu and Mr. Zezhan Zhang. Yi Niu performed the data analyses and made constructive comments by reviewing the manuscript. All authors read and approved the manuscript.

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Data Availability All data generated or analyzed during this study are included in this published article.

Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Conflict of Interest The authors declare that they have no competing interests.

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