**Arthropod-Metamerism-Inspired Resonant Piezoelectric Millirobot**

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Miniaturization, fast motion, high resolution, high agility, and good adaptability are relatively contradictory characteristics in mobile robot design. It is indeed a challenge to satisfy these performances at the same time. Inspired by the arthropod metamerism in nature, herein, a millirobot composed of three piezoelectric segments is proposed. The millirobot is tethered for power, and the whole size of the millirobot is $58 \times 44 \times 12$ mm; it uses several principles of arthropod locomotion, can carry loads and cross obstacles, and also has the rapidity and agility like a centipede through the coordination of multiple piezoelectric segments. Fast motion with a maximum speed of $516$ mm s$^{-1}$ is achieved by operating at resonant mode, and stepping motion with a resolution of $0.44 \mu$m is achieved by the pulsed sinusoidal mode. The widest speed range among published reports of millirobots is achieved (from $4.5 \times 10^3$ to $9$ BL s$^{-1}$). Its agility surpasses other piezoelectric millirobots; the linear, steering, and rotational motions are performed and switched flexibly. The results show that fast motion, high resolution, wide speed range, high agility, large load capacity, good adaptability, and miniaturization are successfully achieved by the millirobot.

1. Introduction

Millirobots have many advantages due to their small sizes and light weight and have become a research hotspot over the past few years. They can not only move and operate in narrow spaces that are unreachable by robots with big sizes or humans, but also be deployed and applied in special environments that cannot withstand large forces due to their light weight; these characteristics favor them as excellent candidate in manipulation, search, and surveillance operations. The traditional millirobots mostly adopt the electromagnetic driving method,[1–6] but their configurations are relatively complicated because transmission systems are usually used to achieve the speed transformation, which limit their miniaturizations. Hence, researchers have tried to develop miniaturized robots with new driving methods and materials. Recent advances mainly include millirobots with materials of dielectric elastomers, shape memory alloys, magnetostrictive materials, etc. Dielectric elastomer millirobots[7–9] need complex stacks and high voltages to realize linear contraction due to the limited strains and deformations, and another challenge is that it is not easy to increase the degree of freedom (DOFs) for locomotion, the agility is limited. Shape memory alloy millirobots[10–12] usually require a long time to cool down, imposing restrictions on bandwidth; the load capacity and response are usually poor. Magnetostrictive millirobots[13–16] need bulky setups to generate the external power sources of magnetic fields and are susceptible to electromagnetic interference. Moreover, millirobots driven by light[17,18] and heat[19,20] have been demonstrated but exhibit slow responses; their output speeds are limited.

Piezoelectric materials have many advantages such as fast response, high resolution, high power density, high bandwidth, self-locking at power-off state, and no electromagnetic interference,[21–26] which are beneficial to realize the miniaturization and improve the output characteristics of millirobots. Robots using thin piezoelectric films have been successfully developed to achieve miniaturization,[27–30] fast motion,[27–29,31] high resolution,[27] good robustness,[30] and high agility.[32,33] However, their applications are limited to some extent because one piezoelectric millirobot can only realize two or three of these characteristics. Therefore, it is a challenge for a single piezoelectric robot to satisfy all the aforementioned characteristics, which is essential to broaden its application.

Inspired by the arthropod metamerism in nature, we propose a piezoelectric millirobot composed of three piezoelectric segments, and the millirobot is tethered for power. The millirobot can achieve characteristics of miniaturized structure, fast motion, high resolution, high agility, and wide speed range simultaneously; the adaptability resembling centipede is also obtained and it can carry loads, climb slopes, and cross obstacles. Specifically, the proposed resonant piezoelectric millirobot achieves several key advancements. 1) Using the continuous and pulsed sinusoidal excitation schemes, the robot (length of $58$ mm and weight of $42.55$ g) achieves a high speed of $516$ mm s$^{-1}$
(about 9 BL s\(^{-1}\)), a high resolution of 0.44 μm (about 8e\(^{-6}\) BL), respectively, and fast motion. 2) The speed of the robot can be smoothly adjusted over an ultrawide range from 0.26 to 516.3 mm s\(^{-1}\) (spans 3 orders of magnitude) by the designed excitation schemes—the widest speed range among published reports of millirobots. 3) the speed still remains 60% of the initial speed (without loads) under a load of 200 g (4.7 times of its own weight). 4) the robot can run on several substrates with different roughnesses, search through a transparent tube with different slopes, and cross various obstacles smoothly, demonstrating its excellent adaptability. 5) The robot can not only realize bidirectional linear motion, but also flexibly perform steering and rotational motions, showing high agility. 6) The robot operates at resonant mode with ultrasonic frequency and the noise is avoided; it is conducive to human—machine friendly cooperation.

2. Results

2.1. Structure Design

In this section, we introduce the structure of the millirobot inspired by the arthropod metamerism, as shown in Figure 1. This robot is mainly composed of three piezoelectric segments with the same configuration, and they are directly connected by steel blocks and bolts. (More details on the structure and main geometric parameters are shown in Figure S1, Supporting Information.) The piezoelectric segment is served as the segment of the centipede, named as piezoelectric leg in this study. Each piezoelectric leg consists of eight pieces of lead zirconium titanate (PZT) elements and an integrated structure including the base beam, driving feet, and thin beam. The cross sections of the base beam and the driving feet are designed as square and circular, respectively, which can ensure that the natural frequencies of the horizontal and vertical bending modes of the piezoelectric leg are equal. The eight pieces of PZT elements are bonded on the eight sides of the base beam symmetrically, so that the horizontal and vertical bending vibrations of the piezoelectric leg can be generated by the horizontal and vertical PZT elements, respectively (Figure 2a). The thin beam is designed to not only realize the elastic support of adjacent piezoelectric legs, but also isolate the vibrations between the adjacent piezoelectric legs.

![Figure 1](image1.jpg)

**Figure 1.** Design and structure of the robot. The blue arrow shows the design process of the millirobot: inspired by the arthropod metamerism, the piezoelectric segments of the robot are designed, and the millirobot is composed of three piezoelectric segments, whose 3D model and prototype are shown in the right circle.

2.2. Working Mechanism

The millirobot is driven by the frictions between the driving feet and the operating substrate and can not only realize linear motion (bidirectional), but also perform steering and rotational motions flexibly, and all these motions are achieved through the coordination of the piezoelectric legs. The principle for the linear motion is presented first, as shown in Figure 2b: all the driving feet perform the same spatial elliptical trajectory with different phases, and they alternately drive the robot to move forward or backward by the frictional force like a centipede. The second bending vibrations (Figure 2a) can form the elliptical motions of the driving feet, so that the two feet on both sides of the piezoelectric leg contact the ground alternately as they have a temporal shift of 180°; furthermore, the second bending vibrations are beneficial in improving the speed of the robot as their high frequencies.

Therefore, the generation of the elliptical trajectory is the most important point of the working mechanism according to the earlier presentations. Take one piezoelectric leg as an example, Figure 2c shows the arrangement, electrical connection, and polarization directions of the PZT elements (OY is the horizontal direction and OZ is the vertical direction). Two orthogonal second bending vibrations are excited by applying two AC voltages with a phase shift of 90° and superimposed to form elliptical motions at the two driving feet (Figure 2d shows the trajectory of one driving foot in one period and Section S1, Supporting Information presents the theoretical analysis for the elliptical motion): in 0–1/4 time period, corresponding to part i in Figure 2d, the sinusoidal voltage of phase Z increases from 0 to the peak, and the driving foot vibrates from the initial position to the maximum displacement along OZ direction, whereas the voltage of phase Y decreases from the peak to 0, and the driving foot returns from the maximum displacement to the initial position along OY direction; the superposition of the two orthogonal motions can form elliptical motion (one-quarter of the elliptical trajectory), as shown by the black arrow. In the same way, the elliptical motions corresponding to the rest parts in Figure 2d are formed through periods ii, iii, and iv in sequence, respectively, and the four arc parts in one period can form a complete elliptical trajectory. The motion direction of the driving foot can be reversed very easily by alternating the phase shift of the two AC voltages for the horizontal and vertical motions and obtaining the backward motion of the robot.

The steering and rotational motions (Figure 2e,f) can be achieved by appropriately adjusting the applied voltages and the phase shift among the piezoelectric legs (Figure S2, Supporting Information). The steering motion is achieved by only applying voltages to the PZT elements on one side of the robot: different vibration amplitudes of the driving feet on the two sides will be generated, which means that the two driving feet on one leg will vibrate with different ellipses and generate different driving forces and the side with larger amplitude is outside of the steering motion. The rotational motion is achieved by exciting the opposite steering motions of the front and rear piezoelectric legs, and no exciting signal is applied to the middle piezoelectric leg; the millirobot will perform rotational motion around its central axis as opposite driving forces are generated.
by the front and rear piezoelectric legs; these driving forces have a distance along OX direction and they will generate a torque on the robot finally. Although the millirobot also has six feet, its motions are unlike regular gaits of hexapods, and the differences between them are explained in detail in Section S2, Supporting Information.

2.3. Parameter Optimization

In this section, we use the finite element method (FEM) to optimize the parameters and identify appropriate configurations for the millirobot. Figure S3, Supporting Information shows the analysis process of parameters optimization. 1) modal analyses of a piezoelectric leg are conducted to ensure that the resonant frequencies of the second bending vibrations in the horizontal and vertical directions are above 20 kHz (operating in the ultrasonic range can avoid noise), and the discrepancy between them is within 1% (approaches on how to achieve high resonant frequency can be seen in Section S3, Supporting Information). 2) Transient analyses of a piezoelectric leg are conducted to ensure that the amplitudes of the driving feet reach the micrometer level under a low voltage (10 Vpp), which can guarantee the
effective motion on the operating substrate and high resolution characteristic. 3) Transient analyses on the whole millirobot are conducted to ensure the effective vibration isolation among the three piezoelectric legs. The determined parameters of the millirobot are shown in Figure S1b, Supporting Information, and the corresponding simulation results are shown in Figure S4, Supporting Information. The resonant frequencies of the second bending vibrations of one piezoelectric leg in the two orthogonal directions are 25.918 and 25.877 kHz, respectively, and their difference is about 0.2%. The vibration amplitudes of the driving feet in the two orthogonal directions reach 2.06 and 2.02 μm under voltage of 10 Vp-p, respectively. The amplitudes of the driving feet on the piezoelectric legs without applying voltage are less than 2.5 nm, which illustrate that the thin beam achieves good vibration isolation. The parameter optimization is accomplished to meet the aforementioned desired goals well.

2.4. Output Characteristic Test of the Piezoelectric Leg

The millirobot can move on the operating substrate through the coordination of the three piezoelectric legs, that is to say, the piezoelectric legs determine its performances. Thus, we measure the characteristics of the piezoelectric legs first, including the bending vibration modes and the displacement responses. Figure 3 shows the results (the experiment setups are shown in Figure S5, Supporting Information). The bending shapes of the

![Figure 3](image-url)
piezoelectric leg in the horizontal and vertical directions (OY and OZ) are in good agreement with the second bending modes (Figure 3a,b). The tested resonant frequencies of the second bending modes and the simulation results are shown in Table S1, Supporting Information. We can see that 1) the maximum difference between the tested and simulated resonant frequencies is 0.896 kHz; 2) the maximum difference between the frequencies of the horizontal and vertical second bending modes is 0.191 kHz (<0.75%), which verifies that the support method using the thin beam has little effect on the bending vibrations; and 3) the maximum difference among the frequencies of the three piezoelectric legs is 0.618 kHz (<2.4%), which indicates that the piezoelectric leg prototypes have good consistency.

The tested displacement responses of the driving feet (the phase shift of the two AC voltages is 90° and the amplitude and frequency are 10 Vp-p and 25.5 kHz, respectively) in OY and OZ directions are shown in Figure 3c,d. The vibration amplitudes of the driving foot in OY and OZ directions are 2.36 and 2.24 μm, respectively. The difference of the displacements in OY and OZ directions is only about 5.1%, which verifies that the thin beam has little effect on the bending vibrations. In addition, the motion trajectories of one driving foot in five cycles along OY and OZ directions are shown in Figure 3e, and the sine waveform vibrations are generated. As shown in Figure 3f, the actual trajectory of the driving foot in the YOZ plane is in good agreement with the elliptical trajectory; there is a small deviation in the OY direction, which is caused by the asymmetric clamping during the test process (Figure S5, Supporting Information).

2.5. Velocity Performance of Linear Motion

We measure the velocity of linear motion on the glass surface at first in this section. As shown in Figure 2, the linear motion is achieved by applying two AC voltages with a phase shift of 90° to the horizontal and vertical PZT elements, and there are three parameters for the exciting signals: amplitude (Vp-p), frequency (kHz) and duty factor (for the sinusoidal burst mode), and the output velocity can be controlled by adjusting these parameters.

Figure 4a shows the relationships between frequency and linear velocity of the millirobot under voltages of 10 Vp-p, 30 Vp-p, 50 Vp-p, and 100 Vp-p. We can see that 25.5 kHz is the optimal frequency, and the maximum velocities are achieved, which is approximately equal to the tested resonant frequencies, and the corresponding maximum velocities are 20.4, 202.3, 321.2, and 516.3 mm s⁻¹, respectively (Movie S2, Supporting Information). The optimal frequency corresponding to the maximum speed is different from the resonant frequencies obtained by the FEM analysis and is tested by a scanning laser Doppler vibrometer; an important factor for the discrepancy of the frequencies is that the walking motion of the millirobot in practice involves ground interaction. Then we measure the velocities versus the excitation voltages under different frequencies (Movie S3, Supporting Information), as shown in Figure 4b, and the velocity increases with the increase in the voltage because higher voltage can produce larger amplitudes at driving feet. We can find that there is an approximately linear relationship between the velocity and the voltage amplitude. Moreover, it is clear that the velocities of the robot in forward and backward motions are well consistent, which is helpful to realize the position adjustment of the robot in the precision positioning and transporting application. In the following sections, 25.5 kHz and 50 Vp-p are set as the fixed frequency and voltage, respectively, without special mention.

To further investigate the speed range of the millirobot, we develop a sinusoidal burst mode (Movie S4), whose excitation scheme is shown in Figure 4c.

The voltage and the pulse repetition frequency are set as 10 Vp-p and 10 Hz, respectively, and the duty factor of the burst ranges from 0.1% to 100% of the pulse period (e.g., 50%). Figure 4d shows the average step displacement (the distance of the robot runs in one pulse driving period) with different duty factors. However, these average step displacements cannot be used to calculate the average velocity because there are obvious pauses, as shown in Figure 4e. Here, we define the condition of the average velocity under the sinusoidal burst mode; the condition is that the millirobot has no pause in the motions, which means that all instantaneous speeds are greater than zero. We achieve this condition by increasing the pulse repetition frequency and duty factor, and the measured minimum average speed is 0.26 mm s⁻¹ (the details are shown in Figure S6, Supporting Information). We can find that the maximum and minimum velocities that the millirobot exhibited on a glass substrate are 516.3 mm s⁻¹ (about 9 BL s⁻¹) and 0.26 mm s⁻¹ (about 0.0045 BL s⁻¹), respectively; the ratio between them is as high as 1986, which is the widest speed range among the published reports of millirobots. The velocity experiments also indicate that the velocity of the robot can be smoothly adjusted within the range of 0.26–516.3 mm s⁻¹ by adjusting the parameters of the exciting signals (amplitude, frequency, and duty factor).

2.6. High Resolution and Fast Response

The sinusoidal pulse mode not only controls the velocity of the millirobot, but also enables it to achieve high displacement resolution.

Figure 4e shows that the millirobot moves with an accurate step under 10 Vp-p, and the displacement resolutions reach about 0.44, 0.75, and 2.38 μm under the duty factors of 0.3%, 0.5%, and 1%, respectively; submicrometer displacement resolution is achieved. Higher resolution can be obtained with more precise equipment in theory as piezoelectric element has high resolution in the nanometer level. This characteristic allows the robot to be very suitable for working in precision fields, such as precision positioning and manipulating.

In addition, we test the fast response characteristic by applying the pulse sinusoidal exciting signal, as shown in Figure 4f, and the starting and braking time are measured to be about 44 and 15 ms, respectively. The response is faster than the previous millirobots based on other materials. The excellent fast response characteristic achieved by the proposed millirobot is beneficial for application in the field requiring quick response, such as target tracking in real time.
2.7. Adaptability

Adaptability is essential for mobile robot to operate in different conditions, which determines its application scope. Thanks to the segmented structure inspired by the centipede, the proposed millirobot has exceptional adaptability due to the collaboration of the multiple driving feet. The adaptability characteristic is demonstrated through three tests: 1) running on several substrates

Figure 4. Performance characterization of the linear motion on the glass surface. a) Relationship between the velocity and the frequency under 10, 30, 50, and 100 $V_{pp}$ b) Relationships between the velocities and the voltages under 24.5, 25, 25.5, and 26 kHz. c) Excitation waveform in one pulse under the sinusoidal burst mode at 10 $V_{pp}$ and 10 Hz. d) The distance that the robot runs in one pulse versus the duty factor under the sinusoidal burst mode, named as step displacement; each data point is the mean value of three experimental data. e) Displacement curves measured by laser sensors (shadow band) under duty factors of 0.3%, 0.5%, and 1%, respectively. f) Transient processes of starting and braking under sinusoidal burst mode, the pulse repetition frequency and duty factor are set as 2 Hz and 30%, respectively. The displacement (blue line) is measured by a laser sensor, and the velocity (red line) is calculated by the differentiating the displacement with time.
with different roughnesses, 2) searching through a transparent tube with different slopes, and 3) crossing various obstacles.

In Movie S5, we measure the velocity of the millirobot on different substrates, as shown in Figure 5a, which also proves the consistency of the forward and backward motions. As expected, the roughnesses of the operating substrates affect the velocity of the millirobot: the robot runs slowest on the paper surface with the largest roughness and fastest on the glass surface with moderate roughness; the consistency of the velocity on the marble surface with the least roughness is the best, and it can run easily on the six different substrates; the influence of surface roughness on the motion of robot is concluded as follows: large surface roughness will hinder the elliptical motions of the driving feet and decrease the velocity; small surface roughness will aggravate the slipping phenomenon between the driving feet and the operating surface and decrease the velocity, and it helps to maintain the consistency of the forward and backward velocities. Next, experiments through a transparent tube (Movie S6, Supporting Information) are conducted, in which the contact condition between the driving feet and the operating surface...
becomes the point contact due to the curved surface and circular section, as shown in Figure 5b. Despite this, the velocity of the millirobot reaches 145.6 mm s\(^{-1}\) (2.5 BL s\(^{-1}\)) while searching through the tube with a dip angle of 9.8° (Figure 5c). In addition, the millirobot can cross obstacles including gully, pothole, and bump smoothly (Movie S7, Supporting Information, and Figure 5d). The widest gully that the millirobot can cross is 28 mm, which is 2.3 times the diameter of the driving foot; excellent crossing performance is achieved due to its multi-segment structure and high-speed capability.

2.8. Carrying Load and Dragged Force

As robots are usually used as the actuating units to move some devices or manipulate samples, they have to have certain carrying capability or dragging capability to complete certain tasks. Movie S8 shows the carrying capability of the developed millirobot. The velocity decreases with the increase in the load, as shown in Figure 6a, but its velocity still maintains about 60% of that in the no-load condition under a load of 200 g (4.7 times of its own weight); this characteristic allows it to carry some electronic devices for completing different tasks. The dragged force of the robot can be measured by the component of self-weight along the slope in the climbing motion, as shown in Figure 6b and Movie S8, in which the dragged force reaches 61 mN and the velocity drops to 163.2 mm s\(^{-1}\) while climbing a slope with an angle of 8.5°. It can be concluded that the dragged force is large enough for moving small objects. It should be noted that the effective weight of the robot is reduced by factor of 1-cosθ during the climbing process, but this factor is very small (arguably negligible) for the angle of 8.5°. Thus, we believe that the evaluated dragged force of 61 mN is effective under the angle of 8.5°. In addition, we test the efficiency of the millirobot by the climbing motions with different loads. The efficiency range of the millirobot is from 0.15–0.37%, and it increases with the increase in the load (from 0 to 50 g). The reason may be that the friction condition between the driving feet and the substrate is improved as the load increases, and the driving force is relatively increased. At present, the efficiency of the millirobot is relatively low; the main reason for the low efficiency is that there is energy loss in the electromechanical coupling and friction coupling process, and the energy loss is actually a common problem. Of course, the final efficiency can be increased by replacing materials with a higher electromechanical coupling coefficient or improving the energy conversion efficiency of the friction coupling process, for example, the driving feet can be designed using materials with a larger friction coefficient to increase the power.

2.9. Agility of the Robot

As shown in Figure 2e,f, the robot could perform steering and rotational motions by adjusting the amplitudes and temporal shifts of the excitation voltages applied to the piezoelectric legs appropriately. The steering motion is achieved by the different vibration amplitudes of the driving feet on the two sides of the robot (Movie S9), the turning radius versus the voltage...
amplitude are measured, as shown in Figure 6c, and the minimum turning radius is 181.4 mm under voltage of 25 V_{pp}. It should be noted that the piezoelectric leg is a whole structure including the left and right legs, so the second bending vibration can be obtained by only exciting the piezoelectric elements on one side of the piezoelectric leg, but the amplitudes of the feet on both sides are different. The increase in the amplitude difference is conducive to the completion of the steering motion, so we only excite the piezoelectric elements on one side of the piezoelectric leg to maximize the amplitude difference.

Figure 6d shows the relationship between the rotational speed (Movie S10) and the voltage amplitude; we can see that the rotational speed increases with the increase in the voltage, the maximum speed of 315° s⁻¹ is achieved under voltage of 100 V_{pp}. This is because the rotational motion of the robot is realized by the opposite frictional forces generated by the front and rear piezoelectric legs. The vibration amplitude difference between the two driving feet of one piezoelectric leg increases with the increase in the voltage, so the rotational speed of the robot increases with the increase in the voltage. In addition, there is also good consistency in the velocities of the robot in the forward and backward steering motions, as well as in the clockwise and counterclockwise rotational motions.

3. Conclusion

In summary, we propose a resonant piezoelectric millirobot based on arthropod metamerism in this study, which integrates three independent piezoelectric segments for flexible motions, and the thin beam structure is designed to realize the elastic support and vibration isolation of the adjacent segments. The robot features a miniaturized structure (length of 58 mm and weight of 42.55 g), wide speed range (maximum and minimum velocities are 516.3 and 0.26 mm s⁻¹, spanning three orders of magnitude), high resolution (0.44 μm), agility locomotion (forward, backward, steering, and rotating), fast response (dozens of milliseconds), large carrying capability (4.7 times of its own weight), and dragged capability (61 mN), as well as good adaptability (running on various substrates such as glass, wood, and marble, climbing in a tube, and crossing obstacles). The main aspects of miniature mobile robot performances are summarized and the performance pentagon is made; the comparisons among the proposed millirobot and several piezoelectric robots recently published are presented based on the performance pentagon figure, as shown in Figure 7. We compare the performances of the robots from five aspects: body length, velocity range, load and drag force, resolution, and agility. Among them, body length is the length of robot in the direction of movement; velocity range is the range between the maximum speed and the minimum speed; loads and dragged forces refer to the maximum weights that the robots can carry and the maximum dragged forces achieved; resolution is the smallest step displacement achieved by the robots; and agility is the degrees of freedom of motions achieved and whether they can move forward and backward. It could be seen that the proposed millirobot has outstanding performances, because it satisfies the miniaturized structure, fast movement, high resolution, and agility movement at the same time to a certain extent. Furthermore, it operates at resonant mode with ultrasonic frequency and the noise is avoided (the noise of the previous piezoelectric robots is quite serious as they do not operate in ultrasonic frequency, and it is not conducive to human–machine friendly cooperation). These characteristics allow the robot to have the potential applications in carrying and manipulating objects for both large range and high resolution.

Furthermore, the millirobot not only has good velocity performance under a low excitation voltage of only 10 V_{pp}, but also can carry a load of 200 g (about the mass of a smartphone), which is conducive to achieve the integration of the robot and onboard power for untethered operations in the future. In addition,
several ideas about application and configuration optimization are briefly introduced in Figure S7, Supporting Information.[135] In short, we will focus on the untethered operation and practical applications in the future.

4. Experimental Section

Materials and Fabrication: The prototype was made of the following parts: three piezoelectric segments (named piezoelectric legs), two pairs of steel-connecting blocks (45 carbon steel), several bolts and nuts (304 stainless steel), and a steel sheet (45 carbon steel). Each piezoelectric leg was composed of a leg segment (2A12 duralumin) and eight PZT elements (PZT-4). Figure S8, Supporting Information shows the material composition, fabrication, and assembly processes. The steel sheet, steel blocks, and leg segments were processed by CNC. The PZT elements were coated with sliver on its surface, which was convenient for welding wires to apply exciting signals. Then, the PZT elements were bonded to the leg segments with epoxy glue to fabricate the piezoelectric legs. There were three steps.

1) Bonding: Epoxy adhesive was smeared uniformly on the contact surfaces of the PZT elements and the contact surface of the leg segment.
2) Aging treatment: The PZT elements were arranged on the leg segment as designed, and they were clamped together by precise flat pliers; the PZT elements completely bonded on the leg segment by the epoxy after 24 h.
3) Welding: The wires (silver-plated copper) with a diameter of 1 mm were welded outside PZT elements, and the varnished wires (varnished copper) with diameter of 0.2 mm were used as connections between the millirobot and external power supply. After the fabrication of the piezoelectric legs, they were assembled together using steel blocks, bolts, and nuts to connect the adjacent thin beams of the leg segments. Finally, the steel sheet was assembled to the top of the steel blocks with the bolts.

Measurement Methods of the Robot Efficiency: We utilized the climbing motions to test the efficiency. The gravity component of the robot and the load along the slope were used to approximate the driving force. The power consumption (input power) was measured by a digital power meter (WT210, Yokogawa, Japan). The tested details are shown in Figure S9, Supporting Information.

Measurement Methods of the Robot Velocity Performance: We used two methods to measure the high-velocity and low-velocity motions of the robot, respectively, as shown in Figure S10, Supporting Information. For the high-velocity motions (the excitation voltage was greater than 10 Vp-p), a camera (Huawei P30) with a frame rate of 30 frames per second was used to record the motions. Then, the motion data were obtained by analyzing the video frames, and the detailed acquisition and processing of the data are shown in Figure S11, Supporting Information. For low-velocity motions (the excitation voltage was 10 Vp-p), we used a laser displacement sensor (LK-H020) to collect the motion data. Then, the displacement–time curves were obtained and the velocities were calculated by differentiating the displacements with time.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

arthropod metamerism, high agility, piezoelectric millirobots, submicrometer resolution, wide speed ranges

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