Small insect-scale robots have demonstrated considerable promise in fields such as equipment fault diagnosis, environmental monitoring, scientific investigation, and disaster relief. However, realizing beneficial traits such as high-speed motion, high load capacity, an internal driving source, and environmental suitability in one small robot is still challenging. Inspired by kangaroo hopping, a small robot is designed with a two-mass soft structure and driven by electromagnetic force. With the synergistic effect of the hopping motion, the soft robot displays two unique properties: 1) the loaded speed is larger than the unloaded one (0–10 times its body weight) and 2) by changing the driving frequency, the moving direction of the robot, i.e., forward or backward, can be controlled. In addition, the robot displays multiple leading properties, including a high-motion speed ($\approx$21.5 body lengths s$^{-1}$) and large load capacity ($\approx$32.5 times its body weight), compared to other robots on the same scale. Furthermore, the robot displays exceptional adaptive capabilities under different circumstances: it traverses slopes, rough and soft surfaces, and even maneuvers underwater. The design strategy and dynamic model adopted in this research provide a reference for future designs and lay a solid foundation for the practical application of high-performing small robots.

1. Introduction

Small insect-scale robots show tremendous promise in fields such as equipment fault diagnosis, environmental monitoring, scientific investigation, and disaster relief.\cite{1,2,3} However, these diverse application areas have strict requirements for small robots, including internal driving sources to realize remote control; high-speed motion ability for efficient operation; high load capacity to carry a variety of components, such as driving elements, sensors, and microcameras; and exceptional adaptive capabilities to function in complex environments, such as traversing slopes, rough and soft surfaces, and maneuvering underwater.\cite{1,2,3,4,5,6} Therefore, the driving method of small robots should include features such as fast response, large driving force, and high energy storage. Existing driving methods use piezoelectric,\cite{7,8} dielectric,\cite{9,10} pneumatic,\cite{11,12} humidity,\cite{13,14} thermal,\cite{15,16} or light\cite{17} power sources, among others. Small robots using these driving methods cannot fully satisfy the requirements for practical utilization because of poor load capacity, slow running speed, high driving voltage,\cite{7,8,9,10,11,12,13,14,15,16,17} low energy density,\cite{13,14,17} and inability to eliminate air sources.\cite{11}

In contrast, the electromagnetic driving mechanism features fast response, large driving force, and low driving voltage and is recognized as one of the most promising methods for realizing small robots for practical applications.\cite{18,19,20,21,22,23,24,25,26} Currently, there are three main research directions for robots that use electromagnetic driving mechanisms: 1) using a traditional electric motor as the actuator, which requires a transmission device to output the twisting force; however, this makes it difficult to achieve miniaturization.\cite{23} 2) Constructing small robots with magnetic materials and then driven using external magnetic fields.\cite{21,24,25} Although miniaturization can be achieved through this method, it does not eliminate complex driving devices. 3) Driving devices, which consist of several telescopic driving units made of magnets, coils, and flexible materials;\cite{22,27,28} however, due to the large coils resulting from the low utilization efficiency of the electromagnetic force, miniaturization can still not be achieved with these existing design strategies.

Drawing inspiration from the diverse species in nature is an efficient way to design robots; examples include jellyfish,\cite{31} inchworm,\cite{32} and cheetah-like\cite{33} soft robots. Kangaroos are animals that move in a hopping manner: they can reach speeds of up
Researchers have developed multiple rigid robots based on the hopping mechanism of kangaroos. As shown in Figure 1A, a two-mass hopping model can be used to describe kangaroo hopping. During hopping, the energy of one cycle can be stored by switching between potential and kinetic energy. The stored energy can then be applied to the next cycle, creating high energy efficiency. Moreover, this unique mechanism allows kangaroos to run fast over complex terrains.

In this study, we combined the advantages of electromagnetic driving with the kangaroo hopping mechanism to develop a two-mass soft-structured small robot. A magnet and coil, representing mass blocks $m_1$ and $m_2$ in the two-mass model, respectively, are connected using a silicone body with a cavity structure. After imposing alternating currents on the coil, a motion similar to kangaroo hopping is generated. The developed robot takes full advantage of the electromagnetic driving mechanism and the synergy of the hopping motion to realize miniaturization (its body length is only 2 cm and its weight is 1.46 g). It is distinctive from other robots on the same scale as it can reach speeds of up to 21.5 body lengths s$^{-1}$ and has a load capacity 32.5 times its body weight. Moreover, this robot could also maintain high-speed motion on slopes, rough and soft surfaces, and even underwater, demonstrating excellent adaptive capabilities under different circumstances. Furthermore, the loaded speed of the robot was larger than the unloaded one (0–10 times its body weight); when two robots were assembled, arbitrary direction control was achieved. These unique attributes allow the developed soft insect-scale robot to carry driving components as well as a variety of sensors and detectors for work in complex environments, thereby significantly increasing potential applications.

2. Results

2.1. Structural Design and Soft Robot Fabrication

The structural illustration of our prototype robot, named R1, is shown in Figure 1B. The dimensions of R1 are $2 \text{ cm} \times 1 \text{ cm} \times 0.6 \text{ cm}$; more detailed parameters are shown in Figure S1 and Table S1, Supporting Information. The two-mass soft-structure robot is composed of three parts: a magnet, coil, and silicone body. The magnet and coil are respectively equivalent to mass blocks $m_1$ and $m_2$, as described in the aforementioned two-mass kangaroo-hopping model. The silicone body plays the role of a supporting substrate. This unique structure has two main characteristics. First, the magnet and coil are placed in a dislocated manner. After applying alternating currents on the coil, an alternating electromagnetic force, $F_z$ (along the vertical direction) and $F_x$ (along the horizontal direction), will be produced between the magnet and coil (Figure S3 and Figure S4, Supporting Information); therefore, the soft robot can run in a hopping manner. Second, the cavity structure of the silicone body can accommodate the motion of the magnet and coil, and the slope at the end of the silicone is

Figure 1. Structure design and motion mechanism of the soft robots. A) Hopping model of kangaroo. B) Structural illustration of one robot. C) An optical photo of soft robot R1 on a fingertip. D) A series of pictures obtained from finite element analysis and optical images, recording the movements of robot R1 in one motion cycle, $I_\alpha = 0.20 \text{ A}$, $f_\alpha = 70 \text{ Hz}$. E) Curves of the horizontal ($X$) and vertical ($Z$) displacements of the centroid of R1’s magnet and coil versus time by finite element analysis, $I_\alpha = 0.20 \text{ A}$, $f_\alpha = 70 \text{ Hz}$. F) Curve of the running speed of R1 versus driving frequencies, $I_\alpha = 0.25 \text{ A}$. 
designed to reduce the resistance from the silicon body to the horizontal vibration of the magnet and coil.

To validate the feasibility of this structure, we used ANSYS software to analyze the motion of robot R1. The vibration mode analysis results show that R1 has two vibration modes on the 2D XZ-plane (Figure S5, Supporting Information), and their vibration frequencies were 50 and 70 Hz, respectively. The motion analysis results show that the running speeds of R1 were 7.6 and 15.3 cm s⁻¹ at a driving frequency of 50 and 70 Hz, respectively (Figure S6A, Supporting Information). However, the motion of R1 at f = 50 Hz was unstable, as shown in Movie S1, Supporting Information. Therefore, in this study, primary research on R1 was conducted at a vibration frequency of 70 Hz.

Consider one motion cycle as an example to illustrate the working mechanism of our robot. The successive motion postures of one cycle are shown as states I–V in Figure 1D. The working mechanism of the robot is similar to that of kangaroo hopping, as it can be divided into a ground-touching phase and an aerial phase. In the ground-touching phase (states I–II), the speed of the coil is zero. The repulsive force between the magnet and coil changes to an attractive force (Figure 1E). The friction force Ff and reactive force Fr are from the ground generate resistance on the coil. The sum of the kinetic and potential energies of the magnet is the total energy of the soft robot that is generated in one cycle. In the aerial phase (states II–V), the soft robot hops into the air and moves in a horizontal direction. In states III–IV, the attraction force between the magnet and coil changes to repulsive, and the magnet adjusts its attitude. As shown in Figure 1D, the front end of the magnet and the silicone body are separated at state IV. This is an important factor in guaranteeing the steady state and high-speed movement of the soft robot. In our design, we purposely did not splice the front end of the magnet to the silicone body to avoid the front end coming into contact with the ground too early. A front end that is driven by the magnet during a stage change when flying could lead to motion instability and a decrease in running speed. In fact, a soft robot named R1' whose magnet was fully spliced to the silicone body encountered this problem in the ground-touching phase, as shown in Movie S1, Supporting Information.

Figure 1C displays the robot R1 with a size smaller than that of a fingertip. Its mass is only 1.46 g, and the silicone body was fabricated via injection molding, as shown in Figure S2, Supporting Information. The magnet and coil were spliced on both sides of the internal cavity of the silicone body with silicone glue. We measured the heating curves of the magnet and coil under varying driving voltages (Figure S7, Supporting Information). The results suggest that under a driving voltage amplitude of V_A = 12 V, the steady temperatures of the magnet and coil reached 105 and 170 °C, respectively. For the silica gel body, we used a silica gel with an operating temperature range of −60 to 250 °C (Table S1, Supporting Information); therefore, the temperature durability can be guaranteed. Because the power lead is not a load-bearing structure, there are no signs of easy damage during our testing. The magnet we used, N40UH-NdFeB, can preserve its magnetization at temperatures under 180 °C. Therefore, its electromagnetic force was not affected by high temperatures. These operating conditions prove the durability of our robot.

We tested the running speed of robot R1 with respect to the driving frequencies in a U-type orbit. The results suggest that the speed has two peak values, at 35 and 70 Hz, equivalent to 8.9 and 18.3 cm s⁻¹, respectively (Figure 1F and Figure S8 and Movie S2, Supporting Information). After analysis, we believe that 35 and 70 Hz are two vibration mode frequencies of the soft robot on the 2D XZ-plane. This corresponds to the two vibration modes obtained from a finite element analysis (Figure S5, Supporting Information). We also used a high-speed camera (sample rate of 1000 fps) to record the movements of R1 (Movie S1, Supporting Information) at I_A = 0.2 A and f = 70 Hz. After comparing the successive motion postures of one typical cycle in the optical images (Figure 1D) with those in the finite element analysis, a good consistency was found, which proves our hypothesis. As these two modes are the same as the kangaroo hopping movement mode, they are more conducive to the movement of the robot. Furthermore, when the excitation frequency is at the modal resonance frequency, the energy conversion efficiency of the excitation force will reach its highest value. Accordingly, there are two motion velocity peaks at 35 and 70 Hz.

In fact, the vibration modes of the soft robot (the frequency of running speed peaks) is determined by the structure, the loading mass, the Young’s modulus of the silicone body, and the working environment. In the subsequent sections of this article, we adjusted the excitation signal frequency to the optimal resonant state to test the running speed of the robot in a specific state (the parameters affecting the resonant frequency remain unchanged) and obtained the corresponding maximum running speeds.

2.2. Motion Analysis

Next, we studied the influence of the driving current amplitude and loading mass on the running speed of the robot. Figure 2A shows R1’s speed at different driving current amplitudes I_A. The experimental results coincided with those of the finite element analysis. With an increase in I_A, the speed increases as well. The maximum speed reached was 20.3 cm s⁻¹ at I_A = 0.30 A (Movie S3, Supporting Information). Moreover, Movie S4, Supporting Information, shows that R1 was running steadily when I_A was less than 0.25 A. In Figure S6C and S3A,B, Supporting Information, we can see that a larger I_A results in a larger F_x in a higher hopping height and longer flight time. In addition, because a larger I_A results in a larger F_x, the robot will have a greater horizontal acceleration capability.

To better analyze the fact that the running speed peaked at 0.30 A, we developed a dynamic model (see Section 6), in which the coil was excluded and the silicone body was assumed to be a rigid rope. At a small driving current amplitude, the acting forces of the silicone body can be ignored because they are in a relaxed state. In this case, as concluded from Equation (S5) and (S6), Supporting Information, the relative displacement amplitudes of the magnet and coil centroids in the horizontal and vertical directions, ΔA_x and ΔA_y, respectively, have a positive relationship with the driving current amplitude. When I_A increases, the silicone body is in a taut state and creates resistance in the horizontal −F_xz and vertical −F_yz directions of the magnet,
leading to no further increase in $\Delta A_x$ and $\Delta A_z$. To verify this model, we plotted the correlation curves of $\Delta A_x$ and $\Delta A_z$, obtained from the finite element analysis, in relation to $I_A$ (Figure 2B); the results confirm the performance of our dynamic model. We further analyzed the force conditions of the robot in the ground-touching phase. During this phase, as shown in Figure 2D–F, the relative displacement between the magnet and coil reaches its maximum and the silicone body is in a taut state. The silicone body creates a resistance force $-F_{rz}$ in the vertical direction of the vertical distance $d$ between the magnet and coil ($d = 1.7$ mm). Meanwhile, $F_x'$ creates a resistance force $-F_{rx}$ in the horizontal direction of the silicone body, which would limit the horizontal acceleration capacity of the soft robot significantly and contribute to motion instability in the robot (Movie S4, Supporting Information). Therefore, the running speed of R1 would not increase with an excessive driving current amplitude.

We also tested the speed of R1 with different mass loadings at $I_A = 0.30$ A, as shown in Figure 2C. Surprisingly, we found that the speed of R1 while carrying a load of 5–15 g was larger than that of the unloaded robot; R1 reached a speed of 41.7 cm s$^{-1}$ with a load of 5 g (Movie S3 and Figure S10, Supporting Information). This unexpected result is beneficial for practical applications of soft robots. Two reasons may have contributed to this result.

First, because the horizontal height of the mass center of the magnet decreases with a load of 5 g, the vertical distance $d$ between the magnet and coil decreases, resulting in the motion state of robot R1 becoming more stable (Movie S4, Supporting Information). We calculated the vertical and horizontal components of the electromagnetic force, $F_z$ and $F_x$, respectively, at various vertical distances $d$ (Figure S4C, Supporting Information). The results indicate that the electromagnetic force significantly increases with a decrease in $d$; at $d = 0$ mm, $F_z$ and $F_x$ are 51 and 95 mN, respectively. These two values are more than twice those in the unloaded state ($d = 1.7$ mm). We used the electromagnetic force at $d = 0.3$ mm as the driving force to analyze the motion process of R1 with a load of 5 g using the finite element method (Movie S4, Supporting Information). The simulated horizontal and vertical displacements of the magnet centroid and coil, respectively, are shown in Figure 2G,H. The simulated result shows that the hopping height of the magnet is smaller than in the unloaded state, and this is consistent with our experimental result. Moreover, the error between the simulated speed (41.4 cm s$^{-1}$, Figure S6B, Supporting Information) in the finite element method and the experiment is only 0.7%. Therefore, the

Figure 2. Research on the effects of the driving current amplitude and loading mass on the motion of robot R1. A) Curves of running speed versus driving current amplitude $I_A$, $f = 70$ Hz. B) The relative displacement amplitude $\Delta A_x$ and $\Delta A_z$ of the horizontal and vertical direction between the magnet and the coil versus $I_A$, $f = 70$ Hz. C) Curve of running speed versus loading mass; see driving frequencies in Figure S9A, Supporting Information. D,E) The horizontal and vertical displacement curves of the centroid of the magnet and coil versus time, $I_A = 0.30$ A, $f = 70$ Hz. F) Simulated movement status in the ground-touching phase, selected from the moment at 342 ms in (D,E). G,H) The horizontal and vertical displacement curves of the centroid of the magnet and coil with loading 5 g weight versus time, $I_A = 0.30$ A, $f = 55$ Hz. I) Simulated movement status in the ground-touching phase, selected from the moment at 342 ms in (G,H). Note: for convenient observing of the relative position between the magnet and the coil, the vertical displacement of the magnet centroid in (E,H) is the sum of the results of finite element analysis and the vertical distance between the magnet and the coil ($d = 1.7$ mm).
increase in the electromagnetic force caused by the lowering of the mass center of the magnet plays an important role in increasing the loaded running speed of R1.

Second, the lowering of the mass center of the magnet also effectively limits the relative displacement amplitude \( \Delta z \) for the magnet and coil along the vertical direction, as shown in Figure 2B. Therefore, the silicone body deformation cannot reach saturation during the motion process. In the ground-touching phase, the silicone body is in a relaxed state (Figure 2I) and will not produce resistance forces \(-F_{\text{r}}\) along the horizontal direction to the magnet; this also contributes to the increase in the running speed under mass loading.

From this analysis, we can conclude that, to achieve high-speed running in soft robots, two factors need to be satisfied: 1) the silicone body deformation should not reach saturation to provide the soft robot with a stable motion state and 2) a good hopping ability is required to maintain a longer flight time; simultaneously, a larger horizontal component \( F_{x} \) is required to guarantee a good horizontal acceleration capacity.

Although a larger electromagnetic force would lead to better hopping ability and horizontal acceleration capacity, it would also more likely to lead to the silicone body deformation reaching saturation. A larger mass loading will impose more restrictions on the deformation of the silicone body along the vertical direction; however, the hopping ability and horizontal acceleration capacity would worsen. Because of these two conflicting factors, with an increase in mass loading, the running speed of the soft robot increases initially and then gradually declines.

### 2.3. Structural Parameters

From the previous section, we know that the electromagnetic force significantly increases as the vertical distance between the magnet and coil decreases. Similarly, if the horizontal distance or the geometric structure of the robot changes, the electromagnetic force also changes. To determine the effect of structural change, we fabricated two additional soft robots, R2 and R3. As shown in Figure 3A, the coil was moved 2 mm toward the head for R2, while the coil was moved 2 mm toward the rear for R3. We then tested the running speeds of robots R1–R3 at various driving frequencies; the results are shown in Figure 3B. The results indicate that R1 and R2 reached their maximum speeds at 70 Hz, whereas R3 reached its maximum speed at 45 Hz. This illustrates that changing the position of the coil would have a noted effect on the motion state of a soft robot. Therefore, the next discussion centers on the driving frequencies at which the three robots reached their maximum speeds.

Figure 3C compares the running speeds of robots R1–R3 at various driving current amplitudes. The speed of R2 was greater than that of R1 when \( I_{\lambda} < 0.25 \text{ A} \), but it was smaller when \( I_{\lambda} \geq 0.25 \text{ A} \) (Movie S5, Supporting Information). In the previous section, we noted that high-speed running can be achieved with a good hopping ability and a large horizontal acceleration capacity. By comparing the electromagnetic forces of R1 and R2, shown in Figure S4A,B, Supporting Information, we can see that the vertical component \( F_{z} \) of the electromagnetic force of R2 is greater than that of R1, whereas the horizontal component \( F_{x} \) of R1 is greater than that of R2. Along with the results from Movie S6, Supporting Information, we considered that, under a small current, R2 has a greater \( F_{z} \) and, therefore, a good hopping capability and a longer flight time. In addition, the bottom of R1 is always in contact with the ground; therefore, it must overcome the friction force. Consequently, for \( I_{\lambda} \geq 0.25 \text{ A} \), R1 was faster than R2 because the \( F_{z} \) of R1 could guarantee that it had sufficient hopping height and the \( F_{x} \) of R1 was greater than that of R2. Furthermore, when \( I_{\lambda} = 0.30 \text{ A} \), the silicone body deformation of R2 reached saturation due to overloading \( F_{z} \), which resulted in motion instability and decreased its running speed.

For R3, because it has a smaller electromagnetic force than R1 at an equal driving current amplitude, it has a lower running speed. Moreover, as shown in Movie S6, Supporting Information, although R3 did not lose its stability when \( I_{\lambda} = 0.30 \text{ A} \), the relative displacement amplitudes \( \Delta z \) of the magnet and coil along the horizontal direction reached their maximum values: the magnet and coil would strike more forcefully during the posture adjustment stage than at \( I_{\lambda} = 0.25 \text{ A} \). This led to increased energy consumption and a decrease in speed.

We also tested the load capacity of robots R1–R3, as shown in Figure 3D. The load capacities of R1 and R2 were notably better than those of R3. With low mass loading, R1 had a faster speed than R2; however, when the mass loading increased, the speed of R1 decreased sharply and was surpassed by that of R2. Upon further increasing the load, the speeds of R1 and R2 converged. This is attributable to R1 having a larger \( F_{z} \) than R2, and the \( F_{x} \) of R1 could guarantee sufficient hopping ability at a low mass loading. After increasing the load, the \( F_{z} \) of R1 was no longer large enough to guarantee sufficient hopping ability, making R1 slower than R2. Based on this analysis, the structure of soft robots in future applications can be optimized to achieve the best performance according to the mass loading.

### 2.4. Directional Control

By changing the driving frequency, we could control the running direction of the robot. Figure S11A, Supporting Information, shows the placement method of R1 with a load of 10 g at its maximum running speed. We reconfigured the placement method, as shown in Figure S11B, Supporting Information, and tested the running speed at different driving frequencies: the results are shown in Figure 4A. Notably, we found that the running speed had two peaks. One peak was located at 60 Hz, at which point the robot moved forward. The other peak was located at 45 Hz, at which the moving direction was reversed (Movie S7, Supporting Information). From this analysis, we determined that by adding loading weight, the mass center of block \( m_{1} \) moves backward in the dynamic model, which leads to a backward motion in state II. This property is extremely effective for solving the problem of turning around in a narrow space.

Further, to achieve arbitrary directional control, we joined two R1-type soft robots using a piece of iron sheeting: the assembled structure is shown in Figure 4B. Due to the magnetic effect, the iron sheeting could be attached to the back of the robots. The assembled robots would move forward in a straight line when setting the same running speed for robots I and II. By changing the driving frequency of the robots, the direction (i.e., forward or
backward) of the joined robots could be controlled (Movie S8, Supporting Information). Turning around can also be realized by switching off one of the robots (Movie S8, Supporting Information). Figure 4C shows that the assembled robots could also follow an S-type route. This feature greatly improves the applicability of our robot and indicates that our robot can be assembled as driving units. Further research on this topic will be conducted.

Figure 3. Structure comparison of different robots. A) Structure difference of robots R1–R3. B) Curves of running speeds of robots R1–R3 versus driving frequencies, \( I_A = 0.25 \) A. C) Curves of running speeds of R1–R3 versus driving current amplitude \( I_A \); the driving frequencies are 70, 70, and 45 Hz, respectively. D) Curves of running speeds of R1–R3 versus loading mass, \( I_A = 0.30 \) A; the driving frequencies can be seen in Figure S9A, Supporting Information.

Figure 4. Direction control of the soft robots. A) Curve of the running speed of robot R1 versus driving frequency, \( I_A = 0.25 \) A, loading 10 g weight. B) Structure of the assembled soft robots. C) Optical images showing the assembled robots walking in an S-type route.
2.5. Performance Comparison

Overall, our developed soft robot exhibits better performance than others at the same scale level. The maximum loading mass of R1 was 47.47 g, which is 32.5 times its body weight (Figure 5A, Movie S9, Supporting Information). With a load of 30 g (20.5 times its body weight), R1 still reached a speed of 1.5 cm s\(^{-1}\), as shown in Figure 2D. This considerable load capacity allows the robot to carry not only driving components, but also a variety of sensors and detecting devices, such as minicameras. The energy cost of transport (COT) is another important indicator for evaluating the applicability of robots; the smaller the COT, the better is the performance.\(^{[2,5]}\) The COT of R1 under different mass load conditions, as calculated by Equation (S13), Supporting Information, is below 1000, as shown in Figure 5B. Furthermore, for loads ranging from 5 to 15 g, the COT is less than 100, which is relatively low for soft robots of the same size.\(^{[2,4,5]}\) This indicates that our robot has a relatively high energy efficiency compared with robots of the same scale. Moreover, R2 reached a maximum running speed of 42.9 cm s\(^{-1}\) while carrying a load of 5 g, which is 21.5 body lengths s\(^{-1}\), as shown in Figure S10, Supporting Information. Figure 5C,D compares the absolute and relative running speeds of our robots with other robots at the same scale level. We can conclude that, regardless of whether we consider the absolute or relative running speed, our robots outperform their same-sized peers.\(^{[2,5,7,40–47]}\)

2.6. Other Attributes

In addition to high-speed running and high load capacity, our developed soft robots possess other considerable attributes (Movie S9, Supporting Information). Figure 6A,B shows that the robot can climb a slope; for example, R2 could climb a slope with an angle of 25° while carrying a load of 10 g at a speed of ≈3.5 cm s\(^{-1}\). A speed comparison at different angles and with different loading weights is shown in Figure 6C. The robot could also run at speeds of ≈5.7 cm s\(^{-1}\) with a load of 10 g while underwater, as shown in Figure 6D,E. Furthermore, we tested its running ability on rough roads and on soft sponge (see Figure 6F–H) and obtained speeds of ≈6.0 and 8.4 cm s\(^{-1}\), respectively. These results summarily display the notable adaptability of our robot under different circumstances, which greatly broadens its application prospects.

3. Conclusion

We developed a small electromagnetic soft robot based on the mechanism of kangaroo hopping. The soft robot is a two-mass system composed of one magnet and one coil connected by a silicone body with a cavity structure. By imposing alternating currents on the coil, a motion similar to kangaroo hopping was generated.

Increasing the loading mass of the robot initially increased the running speed of the robot; however, it eventually declined. The maximum running speed and maximum loading mass reached were 21.5 body lengths s\(^{-1}\) and 32.5 times its body weight, respectively, outperforming other robots at the same scale level. The structure of our robot can be further optimized to achieve the best performance according to the loading mass in practical applications. The robot also possesses good environmental adaptability because it can climb a slope with an angle of 25° and run at a high speed on rough and soft surfaces, as well as underwater.
Notably, the driving voltage required to realize the aforementioned performance was only 12 V ($I_a = 0.3$ A). In addition, the developed robot has a relatively high energy efficiency compared with robots of the same scale. These unique attributes allow the soft robot to carry not only driving components but also a variety of sensors and detectors for work in complex environments. By changing the driving frequency, the moving direction of a single robot, i.e., forward or backward, could be controlled, which effectively solves the problem of turning around in a narrow space. In addition, after joining two robots, arbitrary directional control could be achieved, which is significant for the practical application of small soft robots.

In summary, our robot possesses many advantageous attributes, such as a simple structure, easy fabrication, low cost (<0.1 $\), and outstanding overall performance. Therefore, our design could lay a solid foundation for the practical application of insect-scale soft robots.

4. Experimental Section

Structure, Materials, and Fabrication of the Soft Robots: The structure and detailed dimensions are shown in Figure S1 and Table S1, Supporting Information. The electromagnetic force calculation and motion analysis of the robot structure are shown in the Supporting Information. Parameters associated with the magnet (N40UH-NdFeB, Suzhou Jinci Magnetic Industry Co., Ltd), coil, and silicone (polydimethylsiloxane, PDMS, 4012, Dongguan Xinhong Rubber Industrial Co., Ltd) are shown in Table S1, Supporting Information. The silicone body was fabricated via injection molding; the curing temperature and time were 100 °C and 20 min, respectively. An LCD Photo-Curing 3D Printer (Photon S, Shenzhen Anycubic Technology Co. Ltd) was used to make the mold; its structure is shown in Figure S2, Supporting Information. The material of the mold was VAN-LHTS Photosensitive Resin (Yihui Casting Technology Co., Ltd). Finally, the magnet and coil were spliced on the silicone body using silicone glue.

Driving and Test Equipment: The function signal generator (DG1022Z) and oscilloscope (DS1102E) were purchased from Rigol Technologies, INC. The power amplifier, LYD-304, was from Nantong Longyi Electronic Technology Co. Ltd. The data acquisition card, YAV-16AD, was from Wuhan YAV Electronics Technology Co. Ltd. Finally, the high-speed camera, MV-A5031M815, was from Zhejiang Dahua Technology Co., Ltd.

Driving Current Application: The driving signal issued by the function signal generator was applied to the coil after amplification via a power amplifier. The current and voltage measuring ports were integrated with the power amplifier, and they were measured by the oscilloscope.

Temperature Measurement: The heating curves of the soft robots were measured by K-type thermocouple temperature sensors and the data were collected by the data acquisition card.

Running Speed Test: To measure the straight-line speed, the soft robots were run on a U-type orbit. The width and depth of the orbit were 11.5 and 6 mm, respectively. For the load capacity test, weights were used as the mass block. They could attach on the back of soft robots due to magnetic attraction. In addition, considering that the weight placement method also affects the modal frequency and running speeds, their placement was adjusted repeatedly to obtain the maximum speed of the robot. Furthermore, measurements were conducted after the driving current amplitude stabilized.

Supporting Information

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

Acknowledgements

This research was supported by the National Natural Science Foundation of China (91648109) and the Natural Science Foundation of Jiangsu Province with grants BK20200984.

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

electromagnetic actuators, high speeds and loads, small robots, soft robots, two-mass soft structures

Received: June 28, 2021
Revised: August 1, 2021
Published online: September 14, 2021

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