Ultrahigh Agility with Trajectory Control of Insect-Scale Soft Robots

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Abstract
Agility and trajectory control are two desirable features for all moving objects but they become very challenging for soft robots without rigid structures to support rapid manipulations. Here, a curved piezoelectric thin film driven at its structural resonant frequency is utilized as the main body of an insect-scale soft robot for its fast translational movements, and two electrostatic foot-pads are employed for its swift rotational motions. These two schemes are simultaneously executed during operations via a simple two-wire connection arrangement. A highest relative centripetal acceleration of 28 body-length/s² among all artificial robots is realized on a 65 mg-tethered prototype, which is better than those of common insects, including the cockroach. The trajectory manipulation demonstration is accomplished by navigating the robot to pass through a 120 cm-long track in a maze within 5.6 seconds. One potential application is presented by carrying a 180 mg on-board sensor to record a gas concentration route map and to identify the location of the leakage source. The radically simplified analog motion adjustment technique enables the scale-up construction of a 240 mg-untethered robot. Equipped with a payload of 1660 mg to include the control circuit, a battery, and photoresistors, the untethered prototype can follow a designated, 27.9 cm-long “S” shape path in 36.9 seconds. These results validate key performance attributes in achieving both high mobility and agility to emulate living agile insects for the advancements of artificial soft robots.

Key Words
Soft robot, Insect-scale, Trajectory manipulation, Mobility, Agility

Summary
Insect-scale soft robots with high agility and trajectory manipulation for tethered and untethered operations.
Introduction

Both agility and trajectory manipulation of all artificial robots are important features toward possible practical applications. Specifically, fast-running robots without the ability to navigate around obstacles by coordinating both speedy translational and rotational motions won’t be able to execute even common tasks in complex environments. These two desirable characteristics become even more challenging for soft robots due to their unique structural constraints of high flexibility, deformability (1, 2), and robustness (3, 4). For example, conventional rigid-body robots can use differential gaits to realize turning motions similar to those in insects (5-10). However, soft robots have difficulty in employing this strategy due to their low structural stiffness, which reduces their ability to manage good motion controls (3, 11-14). Previously, trajectory manipulations of robots based on pneumatic structures with the body length scale of more than 10 cm have been demonstrated with relatively poor agility due to their slow moving speeds (14-17). An insect-scale soft robot has achieved high moving speeds up to 20 body-length/s (BL/s) by its unique structural design and driving scheme, but it has exhibited low agility and poor trajectory controllability (18). Some insect-scale soft robots based on dielectric elastomer actuators (DEAs) have been developed to show various moving trajectory patterns by advanced digital control schemes (19-22). However, a key fundamental challenge in the field of insect-scale soft robots is the ultrahigh agility and good trajectory control that are comparable to those of real agile insects. One application scenario for such a robot is to move quickly like a cockroach by carrying sensors in ruins after disastrous events and to record and transmit valuable information in search and rescue operations. Bio-inspired soft robots having the advantages of flexibility, deformability, and robustness are desirable for these applications but their soft bodies often result in poor agility which limits their functions.

The difficulty in achieving high agility of any robot is to have a very fast linear moving speed while maintaining the capability of making turns. Specifically, a fast-moving robot could lose its stability while executing the turning motions due to the inertia effect. In nature, insects having flexible bodies can dynamically tune the friction force with secretions between their feet and the ground to improve locomotion (23-27). Similar schemes have been emulated in small-scale robots to accomplish various exceptional functions, such as climbing on a vertical wall using the electrostatic force for attachments (7, 19). Inspired by this strategy, a tethered
prototype soft robot has been built by using a curved unimorph piezoelectric film structure as the main body for fast moving speeds, and two electrostatic foot-pads have been implemented for speedy turning motions. The friction force between the electrostatic foot-pads and the ground can be independently adjusted by varying the foot-pad DC bias voltages to regulate the moving trajectory. Key advancements of this work include: (i) the highest relative centripetal acceleration among artificial robots at 28 BL/s² for a 3×1.5 cm²/65 mg tethered prototype with highly robust operations; (ii) a trajectory manipulation demo of a tethered robot to navigate through a 120 cm-long path in a maze in just 5.6 seconds and an application presentation by carrying a 180 mg gas sensor to detect gas leakages; and (iii) a 2.4×2.2 cm²/240mg untethered robot with light-induced motion adjustment controls by carrying a 6.9 times heavier payload (1.66 g, including a battery, photoresistors, and control circuit) to finish a designated, 27.9 cm-long “S” shape path in 36.9 s. In this case, a simplified, two-wire motion adjustment technique enables the easy setup of power electronics for the scale-up untethered robot. The design principles, motion manipulation methodologies, system characterizations, and application demonstrations all aim to advance the field of soft robots with the goal to emulate agile insects toward practical applications.

Results

Design strategy and basic mechanism

An optical image of a tethered, insect-scale soft robot (3×1.5 cm², 65 mg) is shown in Fig. 1A together with a queen ant (Camponotus turkestanus) for size comparison. The fabrication processes are given in Fig. S1 based on the previous work (18) with added electrostatic foot-pads. The robot is composed of a main body, a rear leg, and two front legs with electrostatic foot-pads. The SEM image in Fig. 1B shows the cross-sectional view of the main body made of three polymer layers: the curve-shape piezoelectric Polyvinylidene Fluoride (PVDF, 18 μm) thin film with top and bottom Ti/Au (10/100 nm) electrodes; the silicone adhesive layer (25 μm); and the Polyethylene terephthalate (PET, 25 μm) passive layer at the bottom. Under the excitation of an AC driving voltage at the structural resonant frequency (113-190 Hz for the prototypes with slightly different design and fabrication variations), the curved piezoelectric
unimorph structure can extend and shrink repeatedly to result in the rear leg and the two front legs to strike the ground for fast forward movements (Fig. S2). The electrostatic front foot-pad has the design shape of a droplet and is made of a Polyimide (PI, 5 μm in thickness) film at the bottom with a Ti/Au (10/100 nm) electrode on the top. The total foot-pad area is 32 mm², as shown in Fig. 1C. A PET frame is attached on top of the foot-pad with the help of silicone adhesive as the mechanical support. The electrodes of the right and left foot-pads are connected to the bottom and top electrodes of the piezoelectric unimorph robot body, respectively. The droplet-shaped design is helpful to enlarge the contact area between the foot-pad and the ground surface with little impact on the linear moving speed. The front leg is 4 mm in height and is composed of PET/silicone/electrode/PI. The rear leg is a piece of PET film attached to the tail of the robot’s main body, with a height of 3.5 mm.

In nature, an ant can change the friction force with the ground by secretion, as shown in Fig. 1D, to help its locomotion on smooth or vertical surfaces (28). The agility of the soft robot can be drastically improved by adding two electrostatic foot-pads to adjust its friction force \( f_{\text{shear}} \), as shown in Fig. 1E as:

\[
f_{\text{shear}} = \mu_0 (F_{\text{ad}} + F_n)
\]

where \( \mu_0 \) is the friction coefficient between the foot-pad and the substrate; \( F_n \) is the normal force which is small due to the light weight of the soft robot; and \( F_{\text{ad}} \) is the electrostatic force generated by the applied electrical field, \( E \), on the foot-pad as:

\[
F_{\text{ad}} = \frac{1}{2} A \varepsilon_0 \varepsilon_r E^2
\]

where \( A \) is the contact area between the foot-pad and ground; \( \varepsilon_0 \) is the vacuum permittivity; and \( \varepsilon_r \) is the relative permittivity of the medium between the foot-pad electrode and ground (mainly the PI film). The friction force between an electrostatic foot-pad and three different substrates: paper (printer paper 80 g/m² No. 7378, Deli Inc.), polymer (frosted Polyvinyl chloride - PVC, Foojo Inc.), and metal (InSnBi alloy, DingGuan Inc.), under applied DC bias voltages from -250 to 250 V have been characterized with the setup in Fig. S3A and summarized in Fig. 1F. It is observed that the friction force increases symmetrically with respect to the positive and negative DC voltages and proportionally to the square of the applied voltage as predicted in Eq. (2). The friction force has its maximum value of ±0.9 mN on the
metal substrate (slightly lower at ±0.6 mN for the paper and polymer substrates) under an applied foot-pad DC bias voltage of ±250 V. Furthermore, the high surface roughness of the polymer substrate as compared with those of the other two substrates (Figs. S3C-E) contributes to its relatively high friction force under the zero DC bias voltage.

By adjusting the friction force between the right and left electrostatic foot-pads, the robot can produce movements with adjustable trajectories, including straight, clockwise, and counterclockwise motions. For example, the motion of a prototype robot is adjusted to realize the “L” and “3” trajectory paths on a paper substrate in 1.2 and 1.6 seconds, respectively. By driving at its resonant frequency of 143 Hz for fast moving speeds with agile rotational turning capability in Fig. 1G, the tethered robot achieve a moving speed of 7.81 BL/s and a turning rate of 482°/s, respectively, in these two separated tests.

In general, both small size and light weight could help increasing the agility of the robot. The effective friction coefficient gradient $\Delta \mu/\mu_0$ under an applied voltage on the foot-pad can be derived as:

$$\frac{\Delta \mu}{\mu_0} = \frac{\Delta f}{f_0} = \frac{F_{\text{ad}}}{mg\mu_0} = \frac{Ae_0e_1E^2}{2mg\mu_0}$$  \hspace{1cm} (3)

where $\Delta \mu$ is the difference of friction coefficients before and after an external voltage is applied on the foot-pad; $g$ is the gravitational constant; and $m$ is the mass of the robot. A high gradient value, which is proportional to the electrostatic adhesion force and inversely proportional to the mass, implies that the robot can easily make a turning motion. As such, a large applied voltage together with a low body mass, can increase the agility.
Fig. 1. The design strategy and basic working mechanism. (A) An optical image depicting a tethered soft robot of ultrahigh agility with good trajectory manipulation together with a queen ant (*Camponotus turkestanus*). (B) Cross-sectional SEM image of the main robot body.
(C) Schematic diagram showing the structure of an electrostatic foot-pad. (D) Illustration of an ant changing the friction force with a secretion between its foot and ground. (E) Illustration of the soft robot changing the friction force with the ground by applying a DC bias voltage between the electrostatic foot-pad and ground to generate the electrostatic force. (F) Measured friction force between the electrostatic foot-pad of the robot on paper, polymer, and metal substrates under applied DC bias voltages from -250 to 250 V. (G) Demonstration of a tethered soft robot to follow the “L” and “3” paths at high speeds to illustrate its high agility with good trajectory manipulations.

**Trajectory control strategy**

Fig. 2A shows the schematic diagram of the locomotion adjustment scheme with three key elements: the signal generation module, amplifier module, and robot. Two 180° phase-coupled AC square waves sharing the same ground reference are applied to: (1) the bottom electrode of the main body and the right electrostatic foot-pad; and (2) the top electrode of the main body and the left electrostatic foot-pad, respectively. The AC voltage inputs match the resonant frequency of the prototype robots to result in high moving speeds (18). The rotational motion adjustment is achieved by tuning the DC bias voltages to adjust the left and right friction forces, $f_{sl}$ and $f_{sr}$, on the foot-pads as:

$$f_{sl} = \mu_0 \left( \frac{1}{2} A \varepsilon_0 \varepsilon_r (E_{\text{drive}}(t) + E_{\text{bias}}(t))^2 + F_v \right)$$

$$f_{sr} = \mu_0 \left( \frac{1}{2} A \varepsilon_0 \varepsilon_r (E_{\text{drive}}(t) - E_{\text{bias}}(t))^2 + F_v \right)$$

where $E_{\text{drive}}(t)$ and $E_{\text{bias}}(t)$ are the electric fields between the electrostatic foot-pad and substrate from the applied AC driving voltage and DC bias voltage, respectively. Analytically, the main body contracts and extends following the applied AC voltages between the top and bottom electrodes without being affected by the DC bias voltage. On the other hand, the total voltage applied on the foot-pad is the combination of the AC voltage applied on the main body and the DC bias voltage to generate the asymmetric friction effects on the left and right foot-pads to regulate the turning motions. While it is possible to add more electrical wires to independently connect and regulate the body and foot-pads, this two-wire scheme reduces the complexity of the wiring setup and power electronics.
Fig. 2. Trajectory adjustment strategy. (A) Schematic diagram of the locomotion adjustment scheme with three key elements: the signal generation module, amplifier module, and robot. The top electrode of the unimorph robot body is connected to the left electrostatic front foot-pad (orange color) and the bottom electrode of the unimorph robot body is connected to the right electrostatic front foot-pad (blue color). The turning motion adjustments for: (B) straight, (C) clockwise (right turn), and (D) counterclockwise (left turn) motions, respectively, for one-
cycle of different voltage adjustment schemes (top figures), with experimental results within a period of 100 ms (bottom figures). (E) A clockwise rotation in 0.4 s with a small turning radius of 0.82 cm and a counterclockwise rotation in 0.28 s with a small turning radius of 1.07 cm; and (F) A 180-degree “U” turn in 1.3 s.

Figs. 2B, 2C, and 2D show the applied AC voltage in one-cycle and different DC bias voltages of zero, positive, and negative values for one cycle to produce straight, right turn, and left turn motions, respectively. Under a zero DC bias voltage, the robot moves straight forward as the friction force on the right and left foot-pads are equal during the first-half period (body extension when the bottom electrode is under a positive voltage via the blue electrical line) and the second-half period (body contraction when the top electrode is under a positive voltage via the orange electrical line). The electrostatic foot-pad design will not slow down the moving speed when compared with those of soft robots without foot-pads in the previous work (18), which is important to achieve the high agility. Specifically, for a 3-cm-long robot in the previous work, the moving speed was 1.33 BL/s (18) and under the same 200 Vpp driving voltage, this work achieves 1.65 BL/s (Fig. S7A). Under a positive DC bias voltage and in the first-half period of the AC driving voltage, a higher voltage (AC + DC bias) and friction force will be acting on the right electrostatic foot-pad when compared with the voltage (AC – DC bias) and resulting friction force acting on the left electrostatic foot-pad. As such, the right foot-pad becomes a pivot point due to a high friction force and the extension of the robot body will induce a net clockwise torque in this period. In the second-half period, the robot is under contraction and a higher absolute voltage magnitude of “-AC – DC bias” and friction force will be acting on the left electrostatic foot-pad as compared with the absolute voltage magnitude of “-AC + DC bias” and resulting friction force acting on the right electrostatic foot-pad. The left foot-pad now becomes a pivot point with a high friction force and the contraction of the robot body will induce a net clockwise torque in this period. In other words, both periods will produce clockwise rotation. Conversely, under a negative DC bias voltage, a counterclockwise motion will be generated. An analytical model has been established in the supplementary material with numerical simulations to analyze these turning motions (Figs. S10, S11, and S12) together with high-speed camera images and videos by a setup in Fig. S4. The details of straight (movie
S1), right turn (movie S2), and left turn (movie S3) motions of a tethered prototype in a time scale of 100 ms are summarized at the bottom figures in Figs. 2B, 2C, and 2D, respectively. Testing results for longer operation periods have also been recorded, such as straight forward movements for 13.5 cm in 0.6 s with a relative speed of about 7.5 BL/s (Fig. S5A and movie S4), and 90-degree right and left turns with a radius of 9.1 cm and 8.8 cm in 0.6 s (Fig. S5B/movie S5 and Fig. S5C/movie S6), respectively. Several tests have also been conducted on the paper substrate to demonstrate the high agility of the prototype robots with Vpp = 500 V (AC peak to peak voltage) for: (1) clockwise and counterclockwise rotations in 0.4 s and 0.28 s, with a radius/path of only 0.82 cm/2.59 cm and 1.07 cm/2.26 cm, respectively, in Fig. 2E (movie S7 and movie S8); and (2) a 180-degree U-turn in 1.3 s with a path length of 24.4 cm in Fig. 2F (movie S9).

Turning characterization and design optimization

The DC bias voltage and friction coefficient between the foot-pad and substrate (Fig. S3B) can affect the turning performances. Under three different peak-to-peak AC driving voltages (Vpp = 200, 350, and 500 V), we have systematically measured the turning radius (Fig. S6) and relative linear moving speed (Fig. S7) of a prototype robot versus foot-pad DC bias voltages from -250 to 250 V as well as the relative linear velocity versus turning radius (Fig. S8). The optical images of a prototype robot on paper, polymer, and metal substrates are shown in Fig. S9. As the magnitude of the DC bias-voltage increases, the turning agility of the robot increases with reduced turning radius as expected. The metal substrate induces the strongest electrostatic force and the highest friction force to have the smallest turning radius under high absolute DC bias voltages. On the other hand, high AC driving voltages induce large deformations of the robot body to result in fast linear moving speeds, which also contributes to high agility. A figure-of-merit parameter, relative centripetal acceleration \(a_r\), is adopted to evaluate the turning agility quantitatively:

\[
a_r = \frac{V^2}{R \cdot BL}
\]

where \(V\) is the absolute running speed; \(R\) is the turning radius; and \(BL\) is the body length of the robot. The unit of the relative centripetal acceleration is \(BL/s^2\) and a larger value corresponds
to better agility. For the three tested substrates, the relative centripetal accelerations under positive and negative DC bias-voltages are roughly symmetric with small deviations due to manufacturing variations (Figs. 3A, 3B, and 3C). In general, a high AC driving voltage and high absolute DC bias-voltage are preferred to induce a high relative centripetal acceleration. The high AC voltage will result in a high linear moving speed and high relative centripetal acceleration, as observed in Eq. (6). The high absolute DC bias-voltage will result in a large friction force and a reduction in the turning radius to result in a high relative centripetal acceleration. However, if the applied AC driving voltage is low (such as Vpp = 200 or 350 V) and the DC bias-voltage is high (such as 250 V), the relatively small robot body deformations from the low AC driving voltages may not overcome the high electrostatic attraction force on the foot-pads and the turning motion is severely reduced to result in low relative centripetal acceleration as shown in the testing results. In the present setup, the highest relative centripetal acceleration is achieved for a tethered prototype at 28±14 BL/s² under Vpp = 500 V and a DC bias voltage = -250 V on the metal substrate.

Structural designs also affect the relative centripetal acceleration of the robot and the locations of the foot-pads have been investigated as indicated as Point 1 and Point 4 in Figs. 3D and 3E, where x and y represent the distance of the foot-pads to the center of gravity (CG) of the robot body in the x-y coordinate system, respectively. The simulation and experimental results for the relative centripetal acceleration under various combinations of x and y values are shown in Fig. 3F (the detailed simulation setup is explained in the supplementary materials). It is observed that the combination of small x and large y values leads to high relative centripetal acceleration. Qualitatively, the contraction and extension motions of the piezoelectric film can result in a force mainly in the x-direction due to the curved piezoelectric film design. For example, if the body is in the contraction mode and the robot is in the counterclockwise motion in Fig. 3E (Fig. 2D for the contraction mode), the foot-pad at Point 4 will have a higher DC-bias voltage and higher electrostatic force as compared with those at Point 1. This results in a higher friction force \( f_w \) on Point 4 in the positive x-direction as compared to that on Point 1 \( f_d \) to generate a net counterclockwise steering torque \( T_s \) as:

\[
T_s = (f_w - f_d) \times y
\]  

(7)
This explains that a large $y$ value will generate a large net torque by keeping the same values for all other parameters in favor of a high relative centripetal acceleration. On the other hand, there are tangential forces due to the rotation movements of the robot at Points 1 ($f_{rl}$) and 4 ($f_{rr}$) in Fig. 3E, which generate a clockwise resistance torque ($T_r$) as:

$$T_r = (f_{rl} + f_{rr}) \times \sqrt{x^2 + y^2}$$  

(8)

Here, a small $x$ value will reduce this negative (clockwise) torque in favor of a high relative centripetal acceleration in the counterclockwise direction by keeping the same values for all other parameters. This analysis is based on a small size body assumption such that it is not valid for very long robot legs (over 4 mm) and large values of $x$ and $y$ (more than half of the robot’s body length). Experimentally, front pads with four different locations have been designed and tested. It is found that the prototype robot with $x$ and $y$ values of 4.0 mm and 9.7 mm has the best relative centripetal acceleration of 20.9±2.5 BL/s² on the paper substrate and experimental results match well with simulation predictions.

Based on the same model, the size of the electrostatic foot-pad is also analyzed and simulated as shown in Fig. S13. In general, the electrostatic force is roughly linearly proportional to the area of the foot-pad. For foot-pads with a small radius (such as 0.8 mm), the electrostatic force is too small to induce rotational motions. For foot-pads with a large radius (such as 4.8 mm), the electrostatic force is too strong, which can reduce the linear running speed of the robot severely. In both cases, the relative centripetal acceleration becomes very small. As such, the foot-pad size in the prototype robot is chosen to have a radius of 3.2 mm for high relative centripetal accelerations.
Fig. 3. Turning performances on various substrates and foot-pad location studies. Relative centripetal acceleration versus applied foot-pad DC bias-voltage on (A) paper, (B) polymer, and (C) metal substrates, under AC driving voltages, $V_{pp} = 200, 350,$ and $500$ V at the resonant frequencies of the tethered prototype robots and applied DC bias voltages between -250 to 250 V. (D) Simplified dorsal plane model of a robot. (E) Location parameters for the electrostatic
foot-pads. (F) Simulation and experimental results on the paper substrate for the relative centripetal acceleration and electrostatic foot-pad locations. (G) Relative centripetal accelerations of mammals (blue) (29-32), a hummingbird bird (pink) (33), terrestrial arthropods (solid green) (34-39), flying arthropods (hollow green) (40, 41), rigid robots (orange) (5, 42-47), soft robots (gray) (14-17, 19-21, 48-50), and this work (red stars) versus body length.

Animals with high agility tend to have the advantage to survive in the wild (31). A large relative centripetal acceleration means that a robot can run fast and finish a tight turn in a short time. Fig. 3G shows the comparison of the relative centripetal acceleration with respect to the body length for several mammals (blue) (29-32), a hummingbird (pink) (33), terrestrial arthropods (solid green) (34-39), flying arthropods (hollow green) (40, 41), rigid robots (orange) (5, 42-47), soft robots (gray) (14-17, 19-21, 48-50), and this work (red stars). In general, the relative centripetal acceleration reduces as the body size increases due to the increase of inertia effects, which prevent large objects from making quick turns with a small radius when running at high speeds. Several rigid-body robots have demonstrated high agility in the literature but it is very challenging for soft robots as shown in this figure due to the slow running speeds in most published works. This work has increased the relative centripetal acceleration at least one order of magnitude higher than those of state-of-art soft robots. The difficulty in achieving high agility is to have both high linear moving speed and rotational speed. Specifically, a subject with a high linear moving speed may lose the controllability during the simultaneous turning operations due to the inertia effect. It could be even more challenging for soft robots to achieve high agility without differential gaits (5) to realize turning motions due to their low structural stiffness. This work demonstrates the highest relative centripetal accelerations of 28 BL/s² among artificial robots due to the combination of several factors: (1) small size and light weight, (2) strong friction force generated by the electrostatic foot-pads, and (3) high linear moving speeds. We provide a short video clip (movie S10) for the turning motions of a cheetah and our soft robot for the ultrahigh agility demonstration and comparison.
Performance and application demonstrations

To test the robustness of the robot, a box which is 200 times heavier (12.9 g) than the weight of the prototype robot is designed to fall from 50 cm above the ground to hit the tethered robot in Fig. 4A (movie S11). The robot is crushed and flattened by the box but recovers quickly afterward in just 40 ms. Although the moving direction of the robot in this case is changed, the relative speed after the crash remains at 7.7 BL/s without degradation. Moreover, by stepping on a prototype robot with a weight of 55.3 kg by a volunteer, it is found the robot can keep its turning and running capabilities with excellent robustness, as shown in Fig. S14 and movie S12. Another test shows the robot can pass small obstacles by climbing up a 2.4 mm-high step, which is around half of the height of the robot, in 0.29 s as shown in Fig. 4B (movie S13).

Electrical signals with specific sequences have been manually applied to adjust the moving trajectory of a tethered prototype robot to pass through a $51.2 \times 51.2$ cm$^2$ maze, as shown in Fig. 4C (movie S14). A total of 13 continuous motion changes within a total running time of only 5.6 seconds and a total route length of 120 cm have been achieved in this demonstration. The process is recorded with different colors to illustrate the timing of different turning commands on the right side of the figure. Here, the response time of the electrostatic force, which is utilized to realize the turning motions of the robot, is ultra-fast.

A commercial 180 mg gas sensor (TVOC MiCS-5524, SGX), which is about 2.8 times heavier than that of the robot, is added to the prototype robot to execute a gas leakage detecting mission, and the detailed design and measurement schemes are given in Fig. S15. The tethered robot can move at a speed of 7.6 BL/s and 1.2 BL/s under $V_{pp} = 500$ V at the resonant frequency of 143 Hz and 111 Hz without and with the gas sensor, respectively. As indicated in Fig. 4D and movie S15, there is a designated ethanol gas leakage spot in a pipe made of Lego bricks. The robot carrying the gas sensor can complete a designed route with 9 temporary stops (60 seconds at each stop point) to record a gas concentration route map. It is observed that the maximal recorded concentration is 3,869 ppm at point #6, which is in front of the ethanol leakage point. The slightly high concentrations at the starting point and before the ethanol leakage spot are due to the airflow direction and leaks from the Lego constructions. These testing results illustrate key capabilities of the soft robots for potential practical applications, including but not limited to: attaching gas sensors for hazardous gas detections; attaching other
sensors and cameras for sensing and surveillance functions, … etc.

**Fig. 4.** Performance and application demonstrations for a tethered prototype robot: (A) robustness demonstration as a 200 times heavier box falling on the robot from 50 cm above the ground to show the robot has the ability of quick recovery to make normal forward movements; (B) climbing up an obstacle with a step height of 2.4 mm. (C) A tethered prototype robot rapidly passing through a maze in only 5.6 seconds; (D) a tethered prototype robot carrying an ethanol
gas sensor for a leakage detection mission by recording the concentration route map. Inset: the cross-sectional view of the robot carrying a gas sensor.

**Untethered operations**

An untethered version of the soft robot (2.4×2.2 cm², 240 mg) together with a payload of 1.66 g, including a battery (3.7 V, 40 mAh, HuiXinLi, Inc.), two photo sensors (GL3549, JCGL Inc.), and a flexible circuit board, has been constructed to demonstrate the trajectory manipulation and power autonomy, as illustrated in Fig. 5A. The measured resonance frequency is 410 Hz with several slightly different design alternations as compared to that of the tethered robot for better operations, including: (1) the PVDF poling direction is changed from top to bottom; (2) a PI frame is added to the front of the robot to carry the two photoresistors and support the front loads; and (3) two PI supporting structures are added to increase the loading capacity, as shown in Fig. 5B. It is found that if the center of gravity of the robot moves closer to the head position, the linear moving velocity of the robot increases (Fig. S16A). On the other hand, the linear moving speed of the robot decreases as the payload increases as expected (Fig. S16B). Specifically, a prototype without carrying any payload has a linear moving velocity of 3.4 BL/s. The speed decreases to 1.2 BL/s under the payload of 1.66 g (movie S16), and further decreases to 0.4 BL/s with a payload of 2.5 g. Inspired by the antennae navigation and photophobia behavior of insects (51, 52), two photoresistors are utilized to realize the turning function of the robot with an analog control scheme (53) as illustrated in Fig. 5C, with a detailed circuit diagram in Fig. S17A. Specifically, the circuit can output a 500 Vpp driving voltage to the robot’s main body with the left/right photoresistors connected to the top electrode of the main body and the right/left foot-pads, respectively. A foot-pad can be treated as a capacitor and is connected in series with a photoresistor. The voltage amplitude-frequency response on the foot-pad can be calculated as:

\[ A(\omega) = \frac{1}{\sqrt{1 + (\omega RC)^2}} \]  

(9)

where \( \omega \) is the driving frequency; \( R \) is the resistance of the photoresistor; and \( C \) is the capacitance of the foot-pad. A large resistance value of the photoresistor will result in a low voltage on the foot-pad. Under a laser beam, the photoresistor’s resistance drops from 170 kΩ
to 2 kΩ, which can be utilized to regulate the applied voltages on the foot-pads. Specifically, when a laser is pointing at the left/right photoresistor, a 500 Vpp voltage is applied to generate the electrostatic force on the right/left foot-pads for the right/left turns, respectively. **Fig. 5E and movie S16** show one manipulation example of this scheme to realize a designated “S”-shape path on a paper substrate to include straight, left turn (5.6 °/s at a radius of 10.5 cm), and right turn (10.2 °/s at a radius of 6.4 cm) motions. The total time is 36.9 seconds for the robot to complete a 27.9 cm-long path. In the endurance test (**Fig. S17B**), the untethered robot can move for a distance of 31 meters in 19 minutes, which corresponds to an average speed of 27.2 mm/s, **average power consumption of 397 mW, a cost of transport (COT) of 887, with a driving circuit efficiency of 11.8%, and a relative centripetal acceleration of 0.09 BL/s²**. In comparison, the running speed of a previously reported insect-scale soft robot with a payload of 780 mg (including electronics and battery components) is 12 mm/s with a COT of 1670, with a **driving circuit efficiency of 7.5%, and a relative centripetal acceleration at 0.04 BL/s²** (**20**). It is found that most insect-scale robots, such as legged robots and flying robots (**20, 54-56**), have utilized digital control schemes for manipulations and operations. This work uses the analog control scheme for simple operational controls and possible further weight reductions by using lightweight components could lead to more efficient operations.
Fig. 5. Design and performances of an untethered soft robot. (A) An optical photo of an untethered soft robot with a battery, photoresistors, and a flexible circuit (a total weight of 1.66 g). Inset - the flexible circuit. (B) Schematic diagram illustrating the design and assembly of the untethered robot. (C) The output driving signal from the control circuit with photoresistors. (D) Measured voltage on the left and right foot-pad when a laser is irradiating at the left (top) and right (bottom) photoresistors, respectively. (E) Trajectory manipulation demonstration of an untethered robot to complete a 27.9 cm-long, “S” shape path on a paper substrate in 36.9 seconds with the combination of straight, left, and right turn motions adjusted by a laser.
Conclusion

By regulating the friction force of the two electrostatic foot-pads with a simple scheme via two electrical wires with the combination of AC and DC bias voltages, an insect-scale tethered soft robot of excellent robustness has achieved both high moving speeds and turning capabilities for ultrahigh agility and trajectory manipulations. The resulting relative centripetal acceleration of 28 BL/s^2 is the highest among all small soft robots, which is comparable or better than many terrestrial arthropods, such as a cockroach. By carrying a commercial gas sensor, an ethanol leakage detection mission is successfully demonstrated by the tethered soft robot. The study on the relative centripetal acceleration versus body length for state-of-art works from living insects, mammals, and artificial robots has shown that miniaturization is favorable for achieving high agility. The simplified turning regulation scheme helps to reduce the complexity of powering electronics for the construction of an untethered soft robot by integrating a battery, two photosensors, and a flexible circuit. A laser pointer has been utilized to adjust the left/right turns of the robot as an example toward practical applications. While these achievements advance the field of insect-scale soft robots, the grand challenge remains to emulate or even exceed the capabilities of real agile insects. Some possible future directions and challenges include: (i) miniaturizations to further increase the agility; (ii) new design, material, and mechanism to improve the motion trajectory control and increase the payload capacity; (iii) sensors and mechanisms for autonomous feedback controls with speedy responses; (iv) wireless communication systems with low latency wireless link for information exchanges; and (v) on-board energy storage or conversion devices for sustainable long-term operations. These and other supporting efforts could eventually lead to the performance improvements of insect-scale soft robots to match agile insects for the executions of practical and important tasks in various applications.
References


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