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ORIGINAL ARTICLE

An Ultralightweight and Living Legged Robot

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Abstract

In this study, we describe the most ultralightweight living legged robot to date that makes it a strong candidate for a search and rescue mission. The robot is a living beetle with a wireless electronic backpack stimulator mounted on its thorax. Inheriting from the living insect, the robot employs a compliant body made of soft actuators, rigid exoskeletons, and flexure hinges. Such structure would allow the robot to easily adapt to any complex terrain due to the benefit of soft interface, self-balance, and self-adaptation of the insect without any complex controller. The antenna stimulation enables the robot to perform not only left/right turning but also backward walking and even cessation of walking. We were also able to grade the turning and backward walking speeds by changing the stimulation frequency. The power required to drive the robot is low as the power consumption of the antenna stimulation is in the order of hundreds of microwatts. In contrast to the traditional legged robots, this robot is of low cost, easy to construct, simple to control, and has ultralow power consumption.

Keywords: insect-machine hybrid robot, beetle, legged robot, biobot, electrical stimulation

Introduction

Rigid elements used to construct robots constrain their locomotive abilities and limit them to stiff interactions with their surrounding environment. While such robots have high performance and repeatability in predetermined environments, the stiff structure makes it hard for them to adapt to unpredictable environments. On the other hand, robots made of soft materials or combinations of soft and rigid materials have high flexibility and good adaptability to their environments. This makes them more suitable for operating in real-life environments and has led to a surge of interest in soft robotics in recent years.[1–5]

The development of soft robotics relies heavily on examples provided by animal structures and locomotion, such as octopus arms, elephant trunks, kangaroo tails, starfish, fish, and worm and snake bodies.[3,4,6–10] While soft-body-inspired robots are slow and lack precision, for example, those inspired by worms or starfish,[1,3–5,10] the combination of rigid and soft materials may enable the construction of robots with precision of control similar to that of traditional robots, but with higher flexibility and capability, such as that of snakes or fish.[3,7] Pneumatic devices, smart material alloys (SMAs), heat, and living tissues are commonly used as actuators for such robots.[3,11–15] Pneumatic actuators and heat produce fast responses, but they limit the size and mobility of the robots.

Furthermore, the slow response of SMAs limits the speed of the robots, whereas tissue engineering is complicated and limited to certain conditions.[3,11–15] In addition, high power consumption is also a serious issue in soft robotics.[3–5]

Alternatively, it is possible to use a living insect as a platform to develop a living insect–machine hybrid robot. Such a hybrid retains the complex structure of the insect's rigid exoskeleton, compliant joints, and soft actuators, as well as the insect's locomotion capability, and it does so while enabling high controllability and low power consumption. Such an insect–machine hybrid robot is made of a living insect platform with a miniaturized electronic device attached on it to control it. By using the insect itself as the robot, researchers bypass the complex processes of designing and fabricating the robot body, using the insect's muscular system as the soft actuators and flexible joints and its nervous system as part of the control system.[16–25]

Such hybrids not only exhibit high-precision locomotion but also have soft interfaces with the surrounding environment that provide a high level of adaptation. Recent decades have seen the use of these systems in flight initiation/

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cessation, flight steering control, and walking and feedback control of insects.[22,26–28]

The first walking insect–machine hybrid robot, introduced by Holzer and Shimoyama in 1997, included an electronic backpack with two photosensors and an onboard algorithm mounted on a live cockroach to control it to follow a straight line.[23] The robot was not able to follow the line for long time because of using only directional stimulation without optimizing the electrical stimulus. Recently, the Bozkurt group demonstrated a cockroach biobot that can be automatically controlled to follow a curved path with a success rate of 10%, while that of left/right turning was 74%.[24,29] The low success rates would be due to their stimulation protocol, which varied only the stimulation side and fixed the electrical stimulus. Erickson *et al.* demonstrated the graded response of the cockroach behavior by changing the stimulus amplitude with a success rate of 50%.[30] However, tuning the stimulus amplitude would lead to electrode and tissue damage due to electrode oxidation when high levels of charge per phase and high charge density occur and lead to low success rate.[31,32]

To control these cockroach-based robots, an electrical signal was applied to antennae of the live insect to provide the command to steer it in the desired direction. The antenna stimulation triggered the insect's escape mechanism, making it turn to the contralateral side accordingly.[23,24,30] Nonetheless, the current cockroach–machine hybrid robot is not lightweight (3–4 g for the backpack with battery and 6–8 g for the cockroach). The bulky backpack limits their locomotion capability, and the high power consumption for wireless communication (around 90 mW) is a huge challenge for further miniaturization. Although this cockroach-based hybrid robot demonstrated the capability of left/right turning and forward motion, it lacked safe and reliable graded response behavior and backward movement control.[23,24,30]

While graded responses are required for precise motion control, especially when closed-loop control is implemented, the backward movement would enhance the locomotion capability of the living robot, thus helping to produce efficient motion planning for walking control. Besides, one of the targeted applications for the insect–machine hybrid robot is search and rescue missions at disaster sites as it may easily enter the rubble generated. Since rubble size is unpredictable, the smaller the size, the higher the chance the robot can pass through the rubble for a search mission.[33–35] However, scaling down the size of the insect–machine hybrid system is challenging as it depends strongly on the insect platform as well as the electronic components.

Herein, we present an ultralightweight insect–machine hybrid robot with high locomotion capability that challenges other current insect–machine hybrid robots in term of size, weight, and locomotion capability (Fig. 1A). This hybrid robot was developed on a platform consisting of a live beetle, ($\sim$0.5 g) *Zophobas morio*, to which we attached electronic components weighing $\sim$0.45 g. These include a preprogrammed backpack stimulator and two 1.55-V coin-cell batteries (Fig. 1B). The power consumption for wireless communication is about 1.5 mW, whereas that for electrical stimulation is around 180 μW. Electrical pulses were applied to the insect's antennae through working electrodes to cause the insect to turn *through* its escape mechanism. This is the first time antenna stimulation succeeded on the beetle, although it was applied on the cockroach for a long period. We also introduced a safe and efficient protocol to grade beetle responses by fixing the stimulus amplitude and pulse width while varying the pulse frequency.

Such a protocol helped to avoid tissue damage that resulted in a high success rate in turning control (85%) and maintained the long-term performance (5 days) of the living robot. Moreover, we were able to control and grade backward walking of the beetle by alternating left/right antenna stimulation. These graded behaviors and backward walking are necessary for precise motion control and efficient motion planning when a closed-loop control system is required to develop the living robot toward a real search and rescue mission. The small size of our beetle-based living robot (2–2.5 cm) would help it to access small rubbles of disaster sites more easily than the current cockroach-based living robot (5–7.5 cm) in a search mission.

Materials and Methods

Living insect platform

Zophobas morio, also known as darkling beetle, was used as the platform for this insect–machine hybrid robot. The insect is an ideal model for this study because of its relatively small size ($\sim$2–2.5 cm), light weight ($\sim$0.4–0.6 g), and long life span ($\sim$3 months).

Implantation

After being anesthetized using CO_2, the beetle was gently immobilized by clay on a wooden plate. A small hole was bored in the middle of the pronotum using an insect pin (No. 00, Indigo Instruments), and two other holes were created by cutting the antennae. The ends of three Teflon-coated silver wire electrodes (70 μm diameter, bare; 100 μm diameter, coated; A-M Systems) were burned to expose the bare silver wire and then were implanted into the holes to a depth of 2 mm. The electrodes were attached to the beetle's cuticle using melted beeswax. The other ends of the two antenna electrodes were connected to the outputs of the microcontroller or the positive output of the function generator, whereas that of the pronotum was connected to the ground terminal (GND) (Fig. 1B and Supplementary Fig. S1A, B; Supplementary Data are available online at www.libertpub.com/soro).

Wireless backpack stimulator

The insect–machine hybrid robot uses a simple wireless backpack to receive commands and stimulate the beetle. The core of the backpack is a small microcontroller (ATtiny85V, 20 MHz, with 8K of memory). Two outputs are used to generate pulse trains at frequencies of 1–50 Hz for each of the antennae, and one input is used to receive command signals. The infrared (IR) receiver module is connected to this input to receive the IR signal emitted by the computer. One light emitting diode (LED) is connected to each of the outputs to indicate which side is being stimulated (Fig. 1B). The backpack is powered by two coin-cell batteries (1.55 V, 8 mAh). The backpack and batteries are fixed onto the pronotum and elytra of the beetle using beeswax (Fig. 1A).

Motion-tracking system

To evaluate the beetle's response to electrical stimulation, a motion-tracking system[30] was used (Supplementary Fig. S1C,

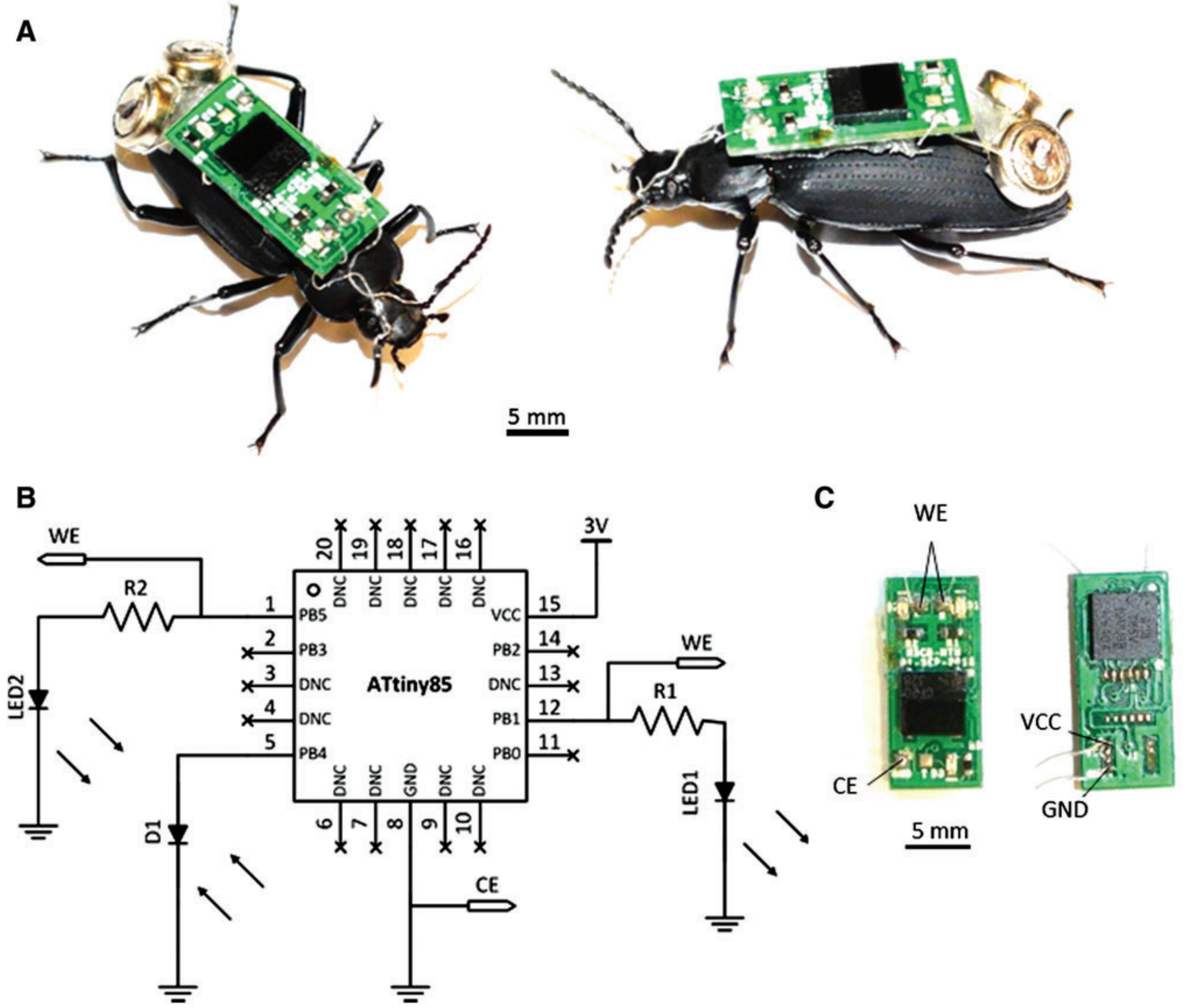

FIG. 1. **(A)** An overview of the insect–machine hybrid robot. A wireless stimulator backpack was mounted on the living insect platform (*Zophobas morio*), with two WE, one implanted in each antenna and one CE implanted in the pronotum of the beetle. **(B)** Schematic of the backpack. **(C)** *Top view* (*left*) and *bottom view* (*right*) of the backpack. CE, counter electrode; GND, ground terminal; VCC, positive power terminal; WE, working electrodes. Color images available online at www.liebertpub.com/soro

D). It consists of the following three subcomponents: (1) a treadmill structure that holds a styrofoam ball, with a miniaxial fan that creates an airbed to support the styrofoam ball to allow the beetle to move freely, (2) two ADNS-9800 laser-optic motion sensors as well as two Arduino microprocessors that feed positional data into a computer, and (3) a data acquisition and control unit comprising a MATLAB user interface that allows for data collection and analysis. The walking trajectories of the wireless-controlled insect (Figs. 2A and 3A) were reconstructed using Digitizing Tools from Hedrick Lab.[36]

Electrical stimulation

Square-wave electrical pulses from a function generator were sent to stimulate the turning response of the beetle. A pulse applied to the left antenna muscle produces a rightward motion, and *vice versa*. Seven different frequencies (1, 5, 10, 20, 30, 40, and 50 Hz) were used to investigate the effects of the electrical signals on the locomotion of the darkling beetle. Once the MATLAB user interface had been initiated, electrical signals of a given frequency and amplitude were applied to the antenna muscles and synced to the MATLAB user interface. The sequence of frequencies used was randomized to prevent bias and to allow the beetle to adapt to changing frequencies. The stimulation voltage and pulse width were fixed at 2.5 V and 2 ms, respectively. The duration of each stimulation trial was 2 s, while a minimum of 1 s was allowed between trials.

Results

The physical contact of the antennae induced high impulses of the mechanosensory interneurons and thus evoked the escape behavior of the insect as the insects use antennae as feelers for navigation.[37,38] The firing rate of the interneurons followed exactly the frequency of tactile stimulus on the antennae[37] and was correlated with the turning angle

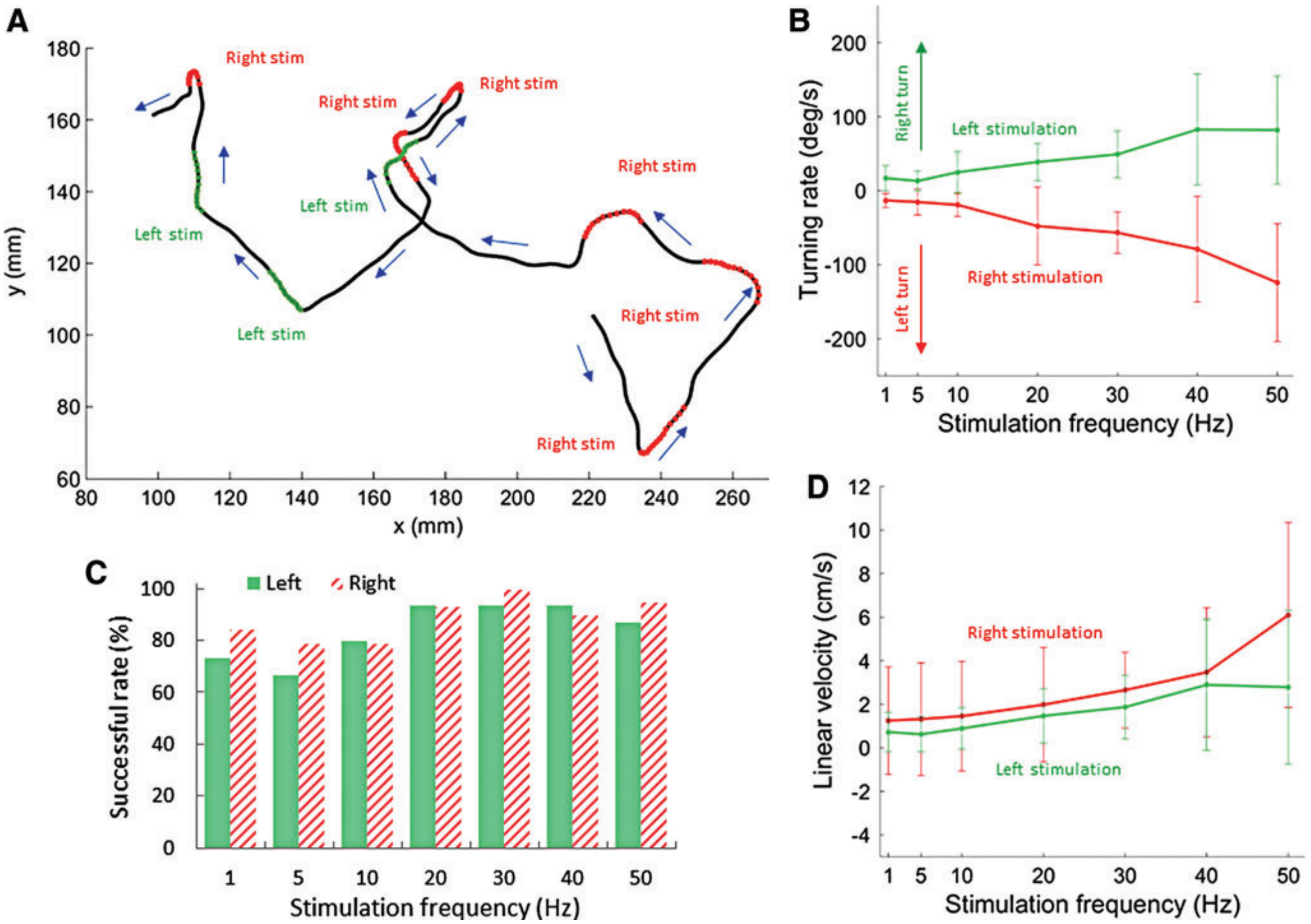

FIG. 2. **(A)** Turning response of the insect–machine hybrid robot when a sequence of *left/right* stimulations was applied. The beetle made contralateral turns when stimulated. *Red* and *green* markers indicate the period of *right* and *left* stimulation, respectively, whereas the *black* line indicates the walking path with no stimulation. *Blue arrows* indicate the direction of the beetle's motion. **(B)** Graded turning response of the beetle. The turning rate increased when the stimulation frequency increased. **(C)** The success rate for stimulated turning. The success rate ranges from about 65% to 80% for stimulation frequencies between 1 and 10 Hz, whereas for the range from 20 to 50 Hz, the success rate is more than 85% (N = 4 beetles, n = 222 trials). **(D)** The velocity change of the beetle due to electrical stimulation. The insect increased its speed when the antennae were stimulated, with the speed increasing with the stimulation frequency. In all cases, the pulse train was set at 2.5 V and 2 ms pulse width. Color images available online at www.liebertpub.com/soro

of the insect, which increased along with the increment of the firing rate.[38] The electrical stimulation of antennae would be able to emulate the tactile stimulus and trigger the escape mechanism of the insect, enabling it to move in the desired direction.[23,24,30] Letting the insect control its own legs helps to preserve its natural locomotion capability. Thus, the insect can perform all the leg movements needed to walk, run, and climb naturally and adaptively. In this way, we save the time otherwise needed to optimize the walking gait of the robot in different environments and reduce both the required memory of the controller and power consumption.[3,4]

Turning in response to electrical stimulation of the antennae

A train of electrical pulses applied to the antennae of the beetle worked as an emulation of an obstacle, biasing the beetle to turn, just as similar signals generated when the antennae touch a real obstacle.[37–43] Stimulation of the right antenna induces a left turn, and *vice versa* (Fig. 2A and Supplementary Movie S1). In addition, the insect exhibits a graded response in turning, increasing its turning rate when the stimulation frequency is increased (Fig. 2B and Supplementary Fig. S2). The beetle showed little reaction to frequencies <10 Hz, with stimulation success rates of 65–80%, whereas the beetles tried to remove the electrodes from their antennae for frequencies beyond 50 Hz. In the range of 20–50 Hz, the success rate in response to stimuli was 85% and above (N = 4 beetles, n = 222 trials). The beetles showed clearly graded responses to electrical stimulation at 10 Hz as the turning rate increased when the stimulation frequency increased (N = 4 beetles, n = 222 trials). The increase in response would be due to rise in the firing rate of mechanosensory interneurons when increasing the antenna stimulation frequency, which drove a stronger reaction of the insect's effort to escape.[30,38] The most effective stimulation response occurred around 300–400 ms after initiation of stimulation. After that period, the insect tried to return to its initial direction, and the turning rates declined and

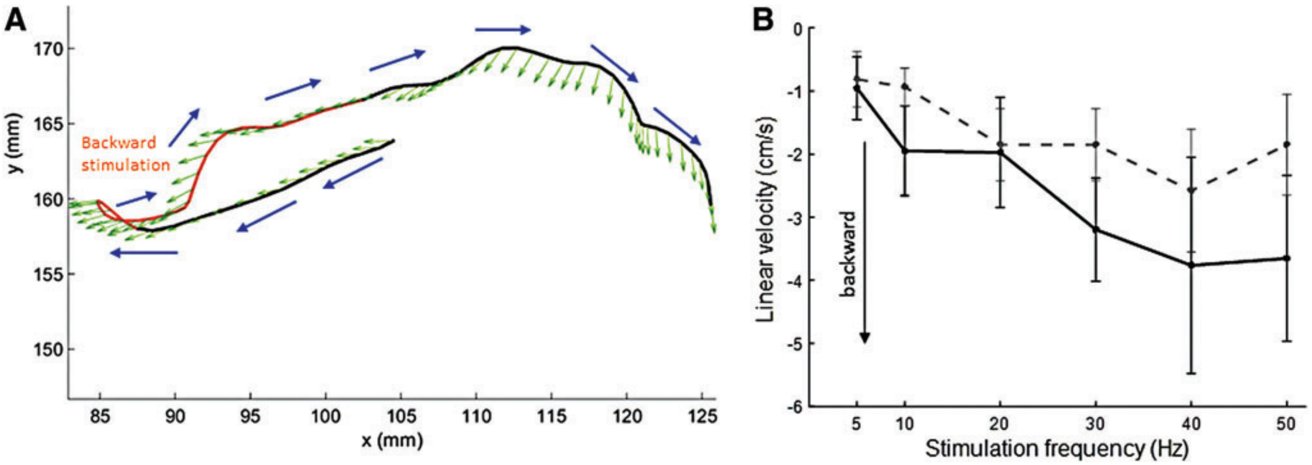

FIG. 3. **(A)** The response of the beetle due to backward stimulation. When backward stimulation was applied, the beetle moved backward while the heading angle remained the same. The *blue arrows* indicate the moving direction of the beetle, while *green arrows* show the heading of the beetle. The stimulation is highlighted in *orange*, while the *black* line is the path without stimulation. The pulse train was set at 2.5 V and 2 ms pulse width. **(B)** The induced backward walking speed due to electrical stimulation. The backward walking speed of the beetles is graded as a function of stimulation frequency. The walking speed when stimulating both antennae (*gray dashed line*) was lower than that when stimulating the antennae alternatively (*continuous black line*). The successful rate of backward walking stimulation is 100% for all frequencies ($N = 4$ beetles, $n = 184$ trials). Color images available online at www.liebertpub.com/soro

fluctuated (Supplementary Figs. S2 and S3). In addition, the beetles increased their walking speeds during electrical stimulation (Fig. 2D). The cause of escape behavior is the insect's tendency to move away from a source of danger.[23,24,40–43] Moreover, the insects were able to maintain the responses to electrical stimulation of antennae for the long term (5 days, $N = 5$, $n = 1058$ stimulations) (Supplementary Fig. S4).

Backward walking

When there is an obstacle in front of the beetle and both antennae touch it, the signals generated from both mechanosensory interneurons cause it to move backward to avoid the obstacle.[38] Similarly, when both the beetle's antennae were stimulated, this emulated signal from both mechanosensory interneurons biased the beetle to move backward (Fig. 3A and Supplementary Movie S2). However, stimulating both antennae at the same time drove the beetles to move backward for a short period of 400 ms, then stop walking for the rest of the stimulation (Supplementary Fig. S5). On the other hand, alternately stimulating the antennae drove the beetle to move backward continuously (Supplementary Fig. S6). This is similar to the natural way an insect approaches obstacles and turns. When one antenna detects an obstacle, the insect turns to the other side and thus senses the obstacle from the other antenna, making it move backward.[40–43] Similar to the turning response, the backward motion was also graded as a function of the stimulation frequency (Fig. 3B).

Low power consumption

The backpack has a low power consumption of about 3 mW during its active mode and 0.6 μW during its sleep mode. The IR receiver requires around 1.35 mW for wireless communication. Furthermore, the power required for electrical stimulation of the antennae is around 180 μW, for a 0.5 s pulse train at 50 Hz, 2.5 V, and 2 ms pulse width. (Supplementary Fig. S7). This is much lower than the power required for conventional actuators made of SMAs and piezoelectric materials. With two coin-cell batteries (SR416SW, 1.55 V, 8 mAh) as the power supply, the system can last for about 8 h in active mode and 41 h in sleep mode. Thus, the insect–machine hybrid robot can travel at most about 1.15 km (with the average speed of the insect at 4 cm/s), which is enough for a rescue mission. Implementing energy harvesting modules such as solar power cells and biofuel cells[44–46] would enhance the lifetime of the backpack, preserving it for more time-consuming tasks.

Limitation

The drawback of the antenna stimulation method is that there is a risk of command failure if an insect chooses the wrong direction or does not follow the command. However, this problem may be solved by using a feedback control system to change the rate of stimulation or a stimulation scheme for precisely steering the insect.

Conclusion

In this article, we have demonstrated an ultralightweight insect–machine hybrid robot exhibiting high locomotion capability and low power consumption. This hybrid robot can be fully controlled by modulating only two parameters: the choice of the left or right side for stimulation and the frequency of the stimulation signal. The living robot was able to perform graded responses and backward walking that are necessary to develop precise motion control and efficient motion planning toward an autonomous living robot for search and rescue. The implantation method and hardware design for this system are simple and can be easily duplicated for mass production. The flexibility provided by employing the insect's own muscular system and joints helps the insect–machine hybrid robot to easily adapt to any unfamiliar terrains. Our preliminary implementation of a wireless control system promotes the development of an insect–machine hybrid robot. Further work on hardware, control systems, and theory may enable the development of controls for more complex behaviors such as swarming.

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Author Disclosure Statement

No competing financial interests exist.

References

1. Bongard JC. Evolving soft robots. Soft Robotics 2016; 3:43–44.
2. Long JH, *et al.* How does soft robotics drive research in animal locomotion? Soft Robotics 2014;1:161–168.
3. Rus D, Tolley MT. Design, fabrication and control of soft robots. Nature 2015;521:467–475.
4. Trimmer B. Soft robots and size. Soft Robotics 2015;2: 49–50.
5. Trimmer MB, *et al.* At the crossroads: interdisciplinary paths to soft robots. Soft Robotics 2013;1:63–69.
6. Horchler AD, *et al.* Peristaltic locomotion of a modular mesh-based worm robot: precision, compliance, and friction. Soft Robotics 2015;2:135–145.
7. Marchese AD, Onal CD, Rus D. Autonomous soft robotic fish capable of escape maneuvers using fluidic elastomer actuators. Soft Robotics 2014;1:75–87.
8. Ming L, *et al.* Slithering towards autonomy: a self-contained soft robotic snake platform with integrated curvature sensing. Bioinspir Biomim 2015;10:055001.
9. Santiago JLC, Godage IS, Gonthina P, Walker ID. Soft robots and kangaroo tails: modulating compliance in continuum structures through mechanical layer jamming. Soft Robotics 2016;3:54–63.
10. Umedachi T, Vikas V, Trimmer BA. Softworms: the design and control of non-pneumatic, 3D-printed, deformable robots. Bioinspir Biomim 2016;11:025001.
11. Akiyama Y, Iwabuchi K, Furukawa Y, Morishima K. Culture of insect cells contracting spontaneously; research moving toward an environmentally robust hybrid robotic system. J Biotechnol 2008;133:261–266.
12. Akiyama Y, Iwabuchi K, Furukawa Y, Morishima K. Electrical stimulation of cultured lepidopteran dorsal vessel tissue: an experiment for development of bioactuators. In Vitro Cell Dev Biol Anim 2010;46:411–415.
13. Akiyama Y, *et al.* Rapidly-moving insect muscle-powered microrobot and its chemical acceleration. Biomed Microdevices 2012;14:979–986.
14. Akiyama Y, *et al.* Atmospheric-operable bioactuator powered by insect muscle packaged with medium. Lab Chip 2013;13:4870–4880.
15. Morishima K, *et al.* Demonstration of a bio-microactuator powered by cultured cardiomyocytes coupled to hydrogel micropillars. Sensor Actuat B Chem 2006;119:345–350.
16. Blaesing B, Cruse H. Stick insect locomotion in a complex environment: climbing over large gaps. J Exp Biol 2004;207: 1273–1286.
17. Delcomyn F. Encyclopedia of Neuroscience. Squire LR (Ed). Oxford: Academic Press, 2009, pp. 479–484.
18. Dickinson MH, *et al.* How animals move: an integrative view. Science 2000;288:100–106.
19. Lipp A, Wolf H, Lehmann F-O. Walking on inclines: energetics of locomotion in the ant Camponotus. J Exp Biol 2005;208:707–719.
20. Sponberg S, Spence AJ, Mullens CH, Full RJ. A single muscle's multifunctional control potential of body dynamics for postural control and running. Philos Trans R Soc B Biol Sci 2011;366:1592–1605.
21. Trimmer B, Issberner J. Kinematics of soft-bodied, legged locomotion in *Manduca sexta* Larvae. Biol Bull 2007;212: 130–142.
22. Cao F, Zhang C, Choo HY, Sato H. Insect-computer hybrid legged robot with user-adjustable speed, step length and walking gait. J R Soc Interface 2016;13:20160060.
23. Holzer R, Shimoyama I. Locomotion control of a bio-robotic system via electric stimulation. In Intelligent Robots and Systems, 1997. IROS '97., Proceedings of the 1997 IEEE/RSJ International Conference on. IEEE, Grenoble, France, vol. 1513, pp. 1514–1519.
24. Latif T, Bozkurt A. Line following terrestrial insect biobots. Conf Proc IEEE Eng Med Biol Soc 2012;2012:972–975.
25. Sanchez CJ, *et al.* Locomotion control of hybrid cockroach robots. J R Soc Interface 2015;12:20141363.
26. Sato H, *et al.* Deciphering the role of a coleopteran steering muscle via free flight stimulation. Curr Biol 2015; 25:798–803.
27. Whitmire E, Latif T, Bozkurt A. Kinect-based system for automated control of terrestrial insect biobots. Conf Proc IEEE Eng Med Biol Soc 2013;2013:1470–1473.
28. Cao F, *et al.* A biological micro actuator: graded and closed-loop control of insect leg motion by electrical stimulation of muscles. PLoS One 2014;9:e105389.
29. Dirafzoon A, *et al.* Biobotic motion and behavior analysis in response to directional neurostimulation. In 2017 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), New Orleans, LA.
30. Erickson JC, Herrera M, Bustamante M, Shingiro A, Bowen T. Effective stimulus parameters for directed locomotion in madagascar hissing cockroach biobot. PLoS One 2015;10:e0134348.
31. Merrill DR, Bikson M, Jefferys JGR. Electrical stimulation of excitable tissue: design of efficacious and safe protocols. J Neurosci Methods 2005;141:171–198.
32. Popovic D, Gordon T, Rafuse VF, Prochazka A. Properties of implanted electrodes for functional electrical stimulation. Ann Biomed Eng 1991;19:303–316.
33. Bozkurt A, Lobaton E, Sichitiu M. A biobotic distributed sensor network for under-rubble search and rescue. Computer 2016;49:38–46.
34. Jayaram K, Full RJ. Cockroaches traverse crevices, crawl rapidly in confined spaces, and inspire a soft, legged robot. Proc Natl Acad Sci 2016;113:E950–E957.
35. Murphy RR, Tadokoro S, Kleiner A. Springer Handbook of Robotics. Siciliano B, Khatib O (Eds). Berlin Heidelberg; Springer International Publishing: 2016. pp. 1577–1604.
36. Tyson LH. Software techniques for two- and three-dimensional kinematic measurements of biological and biomimetic systems. Bioinspir Biomim 2008;3:034001.

37. Ritzmann RE, Pollack AJ. Response of thoracic interneurons to tactile stimulation in the cockroach, Periplaneta americana. J Neurobiol 1994;25:1113–1128.
38. Ye S, Comer CM. Correspondence of escape-turning behavior with activity of descending mechanosensory interneurons in the cockroach, *Periplaneta americana*. J Neurosci 1996;16:5844–5853.
39. Baba Y, Tsukada A, Comer CM. Collision avoidance by running insects: antennal guidance in cockroaches. J Exp Biol 2010;213:2294–2302.
40. Camhi JM, Johnson EN. High-frequency steering maneuvers mediated by tactile cues: antennal wall-following in the cockroach. J Exp Biol 1999;202:631–643.
41. Comer CM, Parks L, Halvorsen MB, Breese-Terteling A. The antennal system and cockroach evasive behavior. II. Stimulus identification and localization are separable antennal functions. J Comp Physiol A 2003;189:97–103.
42. Dürr V, Ebeling W. The behavioural transition from straight to curve walking: kinetics of leg movement parameters and the initiation of turning. J Exp Biol 2005; 208:2237–2252.
43. Ritzmann RE, *et al.* Deciding which way to go: how do insects alter movements to negotiate barriers? Front Neurosci 2012;6:97.
44. Shoji K, *et al.* Insect biofuel cells using trehalose included in insect hemolymph leading to an insect-mountable biofuel cell. Biomed Microdevices 2012;14:1063–1068.
45. Shoji K, *et al.* Insect biofuel cell using an electrode with gold nanoparticles deposited by sputtering. IET Micro Nano Lett 2015;10:674–677.
46. Shoji K, *et al.* Biofuel cell backpacked insect and its application to wireless sensing. Biosens Bioelectron 2016;78:390–395.

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