SOFT ROBOTICS
Volume 1, Number 1, 2013
© Mary Ann Liebert, Inc.
DOI: 10.1089/soro.2013.0002

ORIGINAL ARTICLE

A Hybrid Combining Hard and Soft Robots

Adam A. Stokes,[1] Robert F. Shepherd,[1] Stephen A. Morin,[1] Filip Ilievski,[1] and George M. Whitesides[1,2]

Abstract

This article describes a hybrid robotic system combining hard and soft subsystems. This hybrid comprises a wheeled robot (an iRobot Create; hard) and a four-legged quadruped (soft). It is capable (using a simple, wireless control system) of rapid locomotion over flat terrain (using the wheeled hard robot) and of gripping and retrieving an object (using the independent locomotive capabilities of the soft robot). The utility of this system is demonstrated by performing a mission requiring the capabilities of both components: retrieving an object (iPod Nano) from the center of a room. This class of robot—hybrids comprising hard and soft systems functioning synergistically—is capable of performing tasks that neither can do alone. In contrast to specialized hard robotic arms with grippers (capable of performing some of the functions we describe here), which are complex, relatively expensive, and require sophisticated controls, this hybrid system is easy to construct, simple to control, and low in cost. The soft robotic system in the hybrid is lightweight, disposable if contaminated or damaged, and capable of multiple functions.

Introduction

We are developing a class of pneumatic machines—soft robots[1]—that are modeled on invertebrates such as starfish and octopi.[2] At their present (early) level of development, these soft robots usually move slowly and require pneumatic tethers to a fixed location (e.g., a source of compressed air). They also cannot yet match the load-carrying ability of wheeled or tracked hard robots[3,4] and are unable to carry the weight of their own electropneumatic control system.

Compared with complex and relatively expensive hard robots (e.g., the tracked "packbot" by iRobot,[5] the hard-robotic quadruped by Hirose and Kato,[6] and RHex by Saranli *et al.*[4]), soft robots have several attractive characteristics: mechanical compliance, low cost, simple controls enabled by nonlinear mechanical properties of materials, light weight, low loading of weight-bearing surfaces, and low center of gravity.[1,7] These characteristics may be useful in hazardous, unstable, and toxic environments of the sort encountered after natural disasters and collapsed buildings. To explore and, potentially, to assist in search and rescue operations within these environments, soft robots must be (i) capable of movement on unstable terrain; (ii) capable of directional locomotion; (iii) sufficiently inexpensive that they can be abandoned if damaged or contaminated; and (iv) capable of carrying sensors, imagers, and samplers (as well as, ultimately, other capabilities).

We have developed hybrid systems that integrate soft and hard robots and combine some of the advantages (as well as circumvent some of the limitations) of each class. The hybrid combines a commercially available wheeled hard robot that can carry loads in excess of 2 kg at 0.5 m/s, and a legged soft robot that is slower (~6.5 m/h) but capable of versatile gripping and movement over unstable terrain. This hybrid can be used in a completely untethered mode: It is controlled wirelessly and runs on batteries. The hard robot supplies compressed air to the soft robot through a flexible tether, and also carries the controller, microcompressors, and valves that operate the soft robot.

Here we demonstrate the capabilities of the hybrid by using it to retrieve an object from the center of a room, using only a wireless camera and joystick to control the system. We used the rapid movement of the wheeled hard robot to transport the legged soft robot across a room to the object (an iPod Nano) that we wished to retrieve. We deployed the legged robot to walk to and climb over the iPod, and then used the legs of the robot as a gripper to grasp the object. Finally, we drove the hard robot to a new location and, using it, we dragged the iPod in the grip of the tethered soft robot. The tether in this system both provided compressed air to the soft robot and connected it mechanically to the hard robot.

One feature that distinguishes hard and soft robots is mechanical compliance.[7] Hard robots can be vehicles,[5] arms,

---

[1]Department of Chemistry and Chemical Biology and [2]Wyss Institute for Biologically Inspired Engineering, Harvard University, Cambridge, Massachusetts.

grippers, or multilimbed walking robots.[4,8] Conventional hard robots share four characteristics: (i) they are made of high Young's modulus materials (>100 MPa); (ii) they have a fixed number of axes of motion; (iii) they do not automatically conform to the surface of objects or obstacles; and (iv) they require sophisticated controls to manipulate objects with complex shapes.

Mechanical compliance is an inherent advantage of soft materials, but their actuation for robotic applications has posed unique challenges. Previously reported soft actuators include electroactive polymers,[9] shape-memory alloys,[10,14] and biosynthetic actuators.[15–17] Actuation of electroactive polymers requires high voltages, shape-memory alloys are relatively slow in rapid cycling, and, while biosynthetic actuators have progressed far in the last decade,[15–17] they still require specialized biological processing techniques.

Our soft robots (i) are made of elastomeric materials (<1 MPa Young's modulus) with variable stiffness that depends on the pneumatic pressurization; (ii) can have a nonlinear output motion and variable number of axes of motion[10,14]; and (iii) require only a simple control system to achieve highly complex motions.

Soft robotics and soft machines are rapidly developing fields[6,7] that show promise for applications including gripping, lightweight locomotion, and human–robot interaction. Initial work on soft robotic tentacles by Suzumori *et al.*[18] has been extended by Martinez *et al.*[19] to demonstrate mass transport of acid, sand, and salt using a fluidic network. Pneumatically actuated grippers, using highly extensible elastomers, such as those by Ilievski *et al.*,[20] have been shown, with zero feedback in the control loop, to be capable of picking up delicate objects (uncooked chicken eggs and mice). Feedback when gripping using soft machines is possible using compliant, low-cost sensors such as those by Kramer,[11–13] Mazzeo *et al.*,[21] and Liu *et al.*[22] Systems that use a composite of extensible and inextensible materials have been shown to be capable of complex motion using simple control inputs.[3,18] Shepherd *et al.*[23] demonstrated a soft robot that was capable of locomotion by multiple gaits and demonstrated a robot undulating below an obstacle. Incorporating fluidic networks into locomoting soft robots allowed Morin *et al.*[24] to demonstrate both camouflage and display of soft machines. Recent, nonpneumatic designs of soft robots include the use of shape-memory alloy actuators by Lin *et al.*[15] and the bioinspired approaches using tissue engineering by Nawroth *et al.*[16] and Feinberg *et al.*[17]

Design of the hard robotic subsystem

Here, we used a wheeled hard robot (iRobot Create) to carry a power supply, an electropneumatic control system, and a quadrupedal soft-robotic walker. The wheeled robot, shown in Figure 2, is capable of traveling at up to 500 mm/s (1800 m/h) on a smooth, flat surface.

Design of the electropneumatic control subsystem

We created a control system using readily available, low-power microcontrollers, micropumps, and valves so that it would be inexpensive and able to operate on batteries. We can easily adapt the gait, speed, or direction of the soft robot by using the microcontroller to alter the state and timing of the pumps and valves. The ability to power this system using batteries is important for portability.

The soft robot is controlled using an array of eight microcompressors and eight valves to direct compressed air to each of the eight chambers of the pneumatic networks (pneu-nets) that are embedded within the soft robot. Each pneu-net is actuated/deactuated using one pump and one valve (Fig. 1). We injected compressed air (~7 psi, 0.5 atm, 50 kPa) from each of the eight pump–valve combinations through a silicone tube to each of the pneu-nets. The timing of inflation–deflation of each pneu-net is directed by a program running on a microcontroller. The control system—microcontroller, microcompressors, and valves (Fig. 1c)—runs using the internal rechargeable battery in the iRobot Create (3000 mAh Ni-MH); the system runs for ~1.5 h on a full charge and therefore can be deployed outside the lab.

Design of the soft robotic subsystem

We created a rotationally symmetric soft robot (geometric group C4). The soft robot that we used is a quadruped that is capable of controlled locomotion in four directions at an average speed of 6.5 m/h (Supplementary Fig. S4; Supplementary Data are available online at www.liebertonline.com/soro).

The quadrupedal walker switched between two functions: one locomotive (walking) and one manipulative (gripping). Following the actuation sequence (shown in Supplementary Fig. S6), the robot walked and, by simultaneously actuating all of its legs, functioned like the gripper previously reported (Supplementary Video SV2).[20]

Design of the hybrid system

The hybrid robot, in a marsupial configuration (soft robot carried by hard robot, Fig. 2), allowed us to (i) drive the robots, using wheels, quickly over a flat, hard floor to an object (an iPod Nano); (ii) walk the legged robot over the iPod; (iii) grip the iPod by actuating all four legs at the same time; and (iv) pull it to a different location by driving the hard robot.

Design of the communications system

We designed the communications system, shown in Supplementary Figure S1, to allow us to control both robots, wirelessly, using a joystick (eSecure, USB Dual-Shock Controller) for input. We also mounted a wireless camera (SecurView, TrendNet) on the hard robot: this camera, capable of rotation in two axes, allowed us to operate the robot remotely and did not require us to have a direct line of sight.

Results and Discussion

Fabrication of the soft robot

The quadrupedal soft robot contained two pneu-nets per leg; these actuators allowed us to control the motion of each of the legs, and therefore to drive the robot in four different directions. Acrylonitrile butadiene styrene (ABS) plastic molds were fabricated by fused deposition manufacturing in a Dimension Elite 3D printer. Supplementary Figure S2 provides a technical drawing of the robot. The PN architecture and fabrication methodology is based on the work by Ilievski *et al.*[20] and Shepherd *et al.*[23] We used soft lithography to fabricate the robot using Ecoflex-50 (Smooth-On, Inc.) as the elastomer.

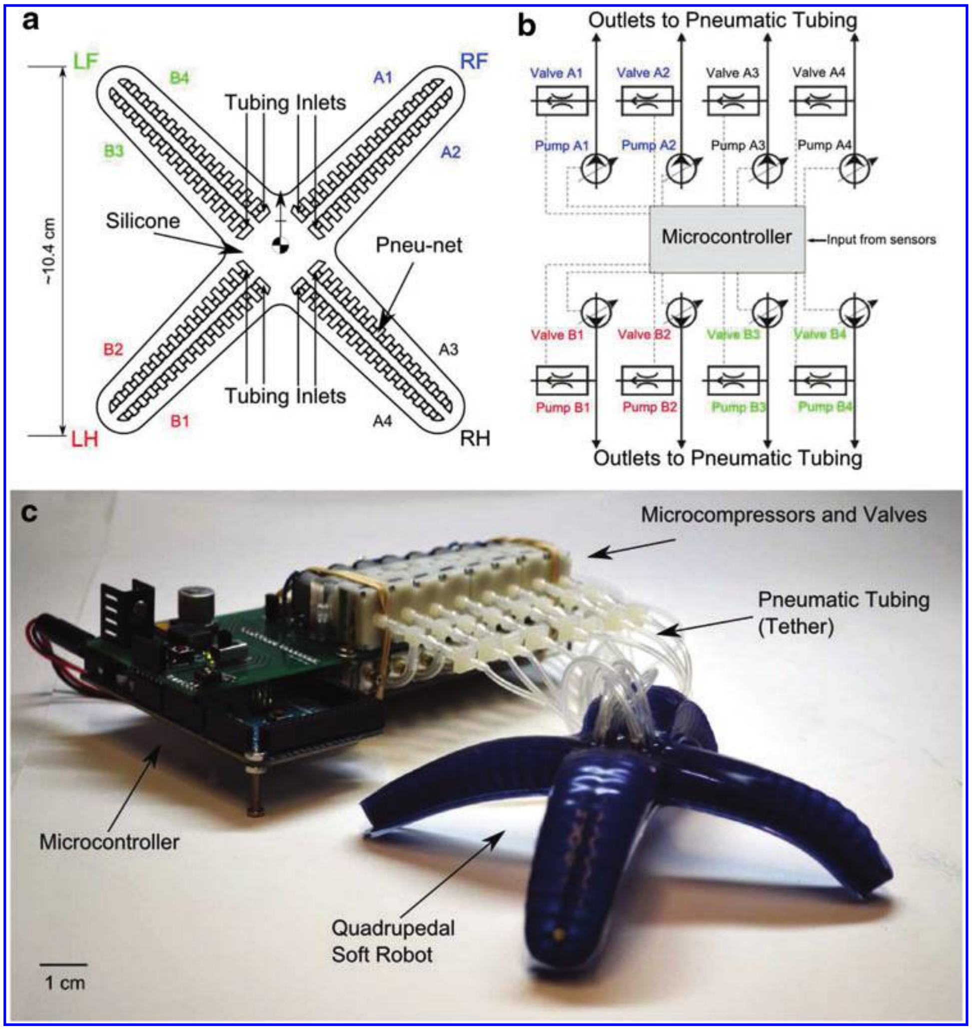

FIG. 1. **(a)** A plan-view schematic of the design of the pneu-net-based quadrupedal soft robot. Each of the four legs contains two independently actuated pneu-nets. A full technical drawing is provided by Supplementary Figure S2. **(b)** A system diagram showing the pneumatic and electrical control system. **(c)** A photograph showing the soft robot, pneumatic tether, microcontroller, and pneumatic control system.

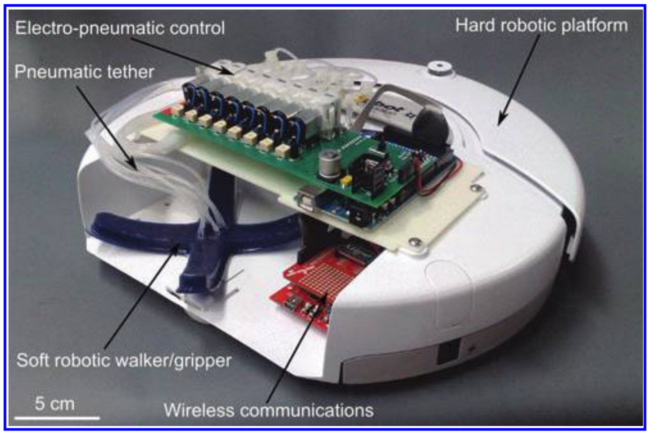

FIG. 2. A photograph of the hybrid robotic platform showing the wheeled hard robot (iRobot Create) and the legged soft robot. The hard robot carried, in marsupial fashion, the legged soft robot, the electropneumatic control system, and the wireless communications system. This figure does not show the wireless camera that was mounted on the hard robot.

Building the hard robotic platform and electropneumatic control

Figure 2 shows the integrated hybrid system. We controlled this robot using custom software running on a microcontroller (Arduino Mega2560) that outputs serial communications based on iRobot's Open Interface Command (OIC) set.[25] Using the OIC, we could (i) control the speed of each of the two wheels; (ii) read information back from the built-in sensors on the robot; and (iii) use our software to control the electropneumatic control system. The electropneumatic control system consists of an array of eight microcompressors and pumps that directed the actuation (inflation/deflation) of the individual pneu-nets in the soft robot. We used the timing of actuation to control the direction of locomotion or to grip an object.

Implementation of the wireless control system

We used XBee (Sparkfun; WRL-08687) as our wireless communications protocol. We read the input from the joystick using a program running a custom-written script (using the processing language: processing.org) on a computer. The program sent serial communications over an XBee link to the wireless communications module (Seeduino Pro & XBee

Shield) mounted on the hard robot. We could drive the wheels of the hard robot using the joystick or switch modes and, using the same joystick, control the motion of the soft robot. (Supplementary Fig. S1 provides a systems overview of the communications and control subsystems.)

Multimode operation of legged robot as gripper

The legged soft robot can also be used to grasp objects (Supplementary Fig. S9). With no sensors on the legs of the robot for feedback, we pressurized all of its actuators to grip a fragile object (a light bulb) without causing damage. This capability is a demonstration of two of the key features of soft robots: multiple functions from a single device and simple control resulting in complex motion with mechanical compliance.

Retrieval of an object

We demonstrated the utility of this hybrid system by using it to retrieve an object: an Apple iPod Nano. Figure 3 shows still frames from Supplementary Video S1. Figure 3a shows the object in the middle of a room. Using the joystick, we drove the hybrid system across the room at its maximum speed (Fig. 3b). In Figure 3c and d, we deployed the soft robot by directing it to walk off the back of the hard robot, and directed it to climb over the iPod. By simultaneously actuating all four legs (all eight pneu-nets) we caused the legged robot to grip the iPod. Finally (Fig. 3e), we showed that, by maintaining the pressure in the soft robot and driving the hard robot away, we could flip the object over, and drag it to a new location. The overturned soft robot acted as a skid and protected the iPod as it was dragged.

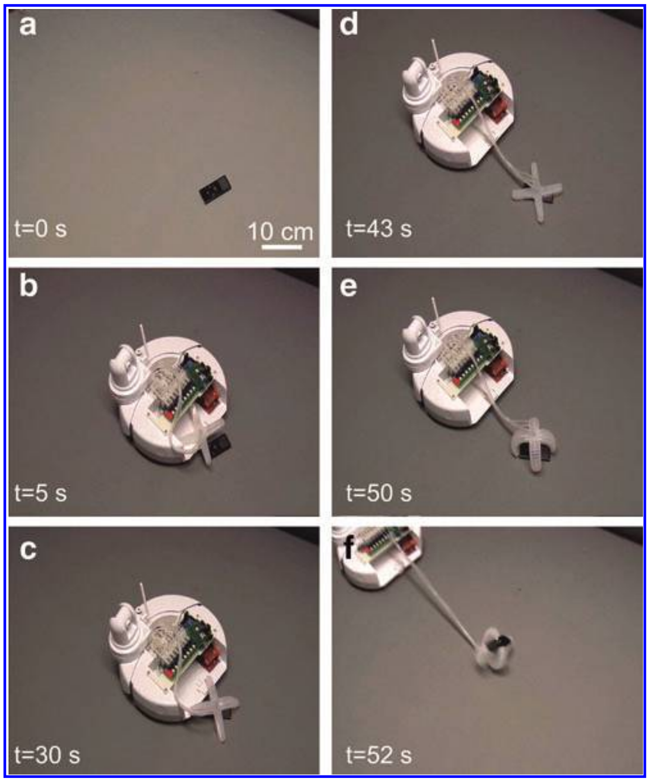

FIG. 3. A series of still frames from Supplementary Video S1 show the hybrid robotic system retrieving an object (iPod Nano) from the center of a room **(a–f)**. The hard robot carries the soft robot to the object **(b)**. The soft robot first acts as a walker **(c–d)** and then as a gripper **(e)**. When the hard robot is driven away **(f)**, the soft robot inverts and protects the iPod as it is pulled to a new location.

Conclusions

The hybrid soft–hard robotic system by Dienno[26] used a mobile hard robotic base with a tethered soft robotic trunk. Our system differs in that we have a multifunctional soft robot that is capable of locomotion that is independent of the hard robotic base unit.

This hybrid system is capable of moving rapidly, with no physical connection to the operator, over smooth surfaces using the wheels of the hard robot and then slowly with the soft robot. The communications system for the hard robot is already well developed. The load-carrying capability of the hard robot enables it to support the components, valves, controllers, and communications systems necessary to run the soft robot. The soft robot is able to walk (although slowly) and to grip irregularly shaped objects. The structure of the soft robot and its connections to the pneumatic tether enable the combined hard–soft system to provide a protective covering of an object during retrieval, and to move it—once gripped—rapidly. This hybrid of hard and soft robots integrates the benefits of both classes of robots. Systems of this type will allow complex tasks to be performed under remote control, using only relatively simple communication and control systems.

Robots that use this hybrid design may find utility in assisted living (e.g., by helping elderly or immobile people retrieve objects from the floor that they would otherwise be unable to reach), in search and rescue, for tasks involving some component of a mechanically weak (e.g., wet sand) or underwater path, when access limits the reach of the hard robot (e.g., when it is required to crawl under barriers), and in operations in hazardous environments.

Retrieval of delicate objects by robots has, previously, required precise motion control and feedback. Our system separates this complex control problem into two components: (i) the hard robot—which provides rapid motion (over compatible terrain, such as a floor) and carries the weight of the electropneumatic components; (ii) the soft robot—which provides a different kind of mobility (e.g., over sand or mud) and the capability for soft, compliant gripping. Our hybrid system shifts the complexity of the system from the design of control software and sensor feedback systems into the physical properties of the soft robot: the requirement for precise control and feedback is removed by the introduction of mechanical compliance.

Hybrid hard and soft robotic systems are capable of performing tasks that neither can do alone. Although it is true that there are specialized hard robotic arms with grippers that could perform the functions we describe here, those systems are complex, relatively expensive, and require sophisticated controls. Our system, by contrast, is (i) easy to construct, (ii) simple to control, and (iii) low in cost. The soft robot in our system is lightweight, disposable if contaminated or damaged, and capable of multiple functions.

Experimental

Soft robot

We purchased Ecoflex-50 from Smooth-on, Inc., and used soft lithography to mold the robots as described by Ilievski *et al.*,[20] Shepherd *et al.*,[23] and Morin *et al.*[24]

Hard robot and electropneumatic control system

We bought a "Create" from iRobot and controlled it using their proprietary OIC set using software that we ran on an Arduino Mega2560 (DigiKey; #1050-1018-ND). The software code is available on request from the authors.

Wireless communications

We made a wireless serial communications link using two XBee units (Sparkfun; #WRL-08687). We wrote a custom script (provided in the Supplementary Materials) using the processing environment to interpret incoming user commands from a joystick (eSecure; USB Dual-Shock Controller) and sent this information over the wireless link to the electropneumatic control system. We bought a wireless camera (SecurView; TrendNet) and used the manufacturer's web-browser interface to control the orientation remotely and to view the on-robot video stream.

Acknowledgment

This work was supported by the Defense Advanced Research Planning Agency Award Number W911NF-11-1-0094.

Author Disclosure Statement

No competing financial interests exist.

References

1. Albu-Schaffer A, *et al.* Soft robotics. IEEE Robot Autom Mag 2008;15:20–30.
2. Sherman IW. The Invertebrates: Function and Form, a Laboratory Guide, 2nd ed. New York: McMillan, 1976, 334 pp.
3. Raibert M, *et al.* Bigdog, the rough-terrain quadruped robot. In: Proceedings of the 17th World Congress of The International Federation of Automatic Control, Seoul, Korea, July 6–11, 2008, pp. 10823–21648.
4. Saranli U, Buehler M, Koditscheck DE. RHex: a simple and highly mobile hexapod robot. Int J Rob Res 2001;20: 616–631.
5. Yamauchi B. PackBot: A Versatile Platform for Military Robotics. Proc SPIE 2004;5422:228–237.
6. Hirose S, Kato K. Development of quadruped walking robot with the mission of mine detection and removal-proposal of shape-feedback master-slave arm. IEEE Int Conf Robot 1998;2:1713.
7. Trivedi D, *et al.* Soft robotics: biological inspiration, state of the art, and future research. Appl Bionics Biomech 2008;5: 99–117.
8. Lee YJ, Bien Z. A hierarchical strategy for planning crab gaits of a quadruped walking robot. Robotica 1994;12:23–54.
9. Guggi K, *et al.* Energy minimization for self-organized structure formation and actuation. Appl Phys Lett 2007;90:081916.
10. Paik JK, Hawkes E, Wood RJ. A novel low-profile shape memory alloy torsional actuator. Smart Mater Struct 2010; 19:125014.
11. Kramer RK, *et al.* Soft curvature sensors for joint angle proprioception. ICROS 2011:1919–1926.
12. Kramer RK, Majidi C, Wood RJ. Wearable tactile keypad with stretchable artificial skin. IEEE Int Conf Robot, Shanghai, China, 2011;1103–1107.
13. Majidi C, Kramer R, Wood R. A non-differential elastomer curvature sensor for softer-than-skin electronics. Smart Mater Struct 2011;20:105017.
14. Seok S, *et al.* Meshworm: a peristaltic soft robot with antagonistic nickel titanium coil actuators. IIEEE Trans Mech 2012;99:1–13.
15. Lin H-T, Leisk GG, Trimmer B. GoQBot: a caterpillar-inspired soft-bodied rolling robot. Bioinspiration Biomimetics 2011;6:026007.
16. Nawroth J, *et al.* A tissue-engineered jellyfish with biomimetic propulsion. Nat Biotechnol 2012;30:792–797.
17. Feinberg A, *et al.* Muscular thin films for building actuators and powering devices. Science 2007;317:1366–1370.
18. Suzumori K, Iikura S, Tanaka H. Development of flexible microactuator and its applications to robotic mechanisms. In: IEEE International Conference on Robotics, Sacramento, California, 1991.
19. Martinez RV, *et al.* Robotic tentacles with three-dimensional mobility based on flexible elastomers. Adv Mater 2012;25: 205–212.
20. Ilievski F, *et al.* Soft robotics for chemists. Angew Chem Int Ed 2011;50:1890–1895.
21. Mazzeo AD, *et al.* Paper-based, capacitive touch pads. Adv Mater 2012;24:2850–2856.
22. Liu X, *et al.* Paper-based piezoresistive MEMS sensors. Lab Chip 2011;11:2189.
23. Shepherd R, *et al.* Multigait soft robot. Proc Natl Acad Sci USA 2011;108:20400–20403.
24. Morin S, *et al.* Camouflage and display for soft machines. Science 2012;337:828–832.
25. iRobot. iRobot Create Open Interface (OI) Specification. 2006. www.irobot.com.
26. Dienno D. Design and analysis of a soft robotic manipulator with base rotation. Master's thesis, University of Pennsylvania, 2006.
27. Buchli J, Ijspeert AJ. Self-organized adaptive legged locomotion in a compliant quadruped robot. Auton Robot 2008; 25:331–347.
28. Williams TL. Experimental analysis of the gait and frequency of locomotion in the tortoise, with a simple mathematical description. J Physiol 1981;310:307–320.
29. Rogers JA, Nuzzo RG. Recent progress in soft lithography. Mater Today 2005;8:50–56.
30. Xia Y, Whitesides GM. Soft lithography. Annu Rev Mater Sci 1998;28:153–337.

Address correspondence to:
George M. Whitesides, AB, PhD
Department of Chemistry and Chemical Biology
Harvard University
12 Oxford Street
Cambridge, MA 02138

E-mail: gwhitesides@gmwgroup.harvard.edu