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Supplementary Materials for

Electronics-free pneumatic circuits for controlling soft-legged robots

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The PDF file includes:

Supplementary Text
Fig. S1. Consistency of the soft ring oscillator.
Fig. S2. Motion of the foot of the robot when the pressure in the pneumatic controller is perturbed.
Fig. S3. Comparison of the speed of the robot while carrying the small (left) and large (right) CO_2 canisters and regulators.
Table S1. List of .stl files.

Other Supplementary Material for this manuscript includes the following:

(available at robotics.sciencemag.org/cgi/content/full/6/51/eaay2627/DC1)

Data S1. Archive of .stl files (.zip format).
Movie S1 (.mp4 format). Video of the African sideneck turtle exhibiting a diagonal couplet walking gait.
Movie S2 (.mp4 format). Video of omnidirectional locomotion, controlled by the four states of two DPDT soft pneumatic switches.
Movie S3 (.mp4 format). Video of robot walking untethered, powered by a pressurized CO2 canister fitted with a pressure regulator.
Movie S4 (.mp4 format). Demonstration of the robot navigating around an obstacle, with manual switching from a single leg pair diagonal gait to a diagonal couplet walking gait, controlled by a dual-purpose three-valve ring oscillator, accelerated 4×.
Movie S5 (.mp4 format). Video of the electronics-free robot autonomously avoiding an obstacle.

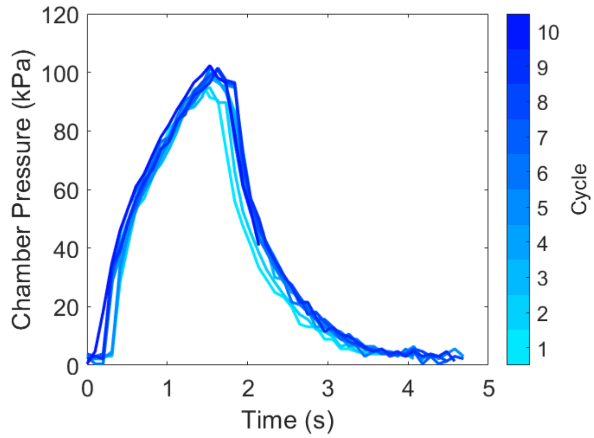

Figure S1: Consistency of the soft ring oscillator. Pressure was measured at one node of the pneumatic circuit for 10 cycles and overlapped to show the consistency in the pressure oscillations in this component of the pneumatic circuit.

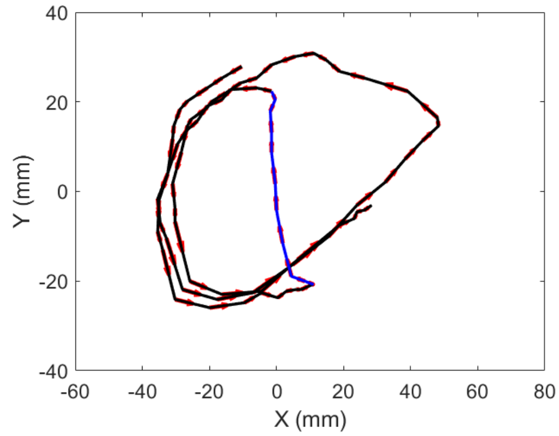

Figure S2: Motion of the foot of the robot when the pressure in the pneumatic controller is perturbed. The position of the foot followed a cyclical trajectory during a normal oscillatory cycle (colored black). After the pneumatic circuit controlling the leg was temporarily perturbed by reducing the input pressure to atmosphere, the position of the foot deviated from the cyclical trajectory (colored blue). When this leak was sealed, the leg returned back to the normal oscillatory movement.

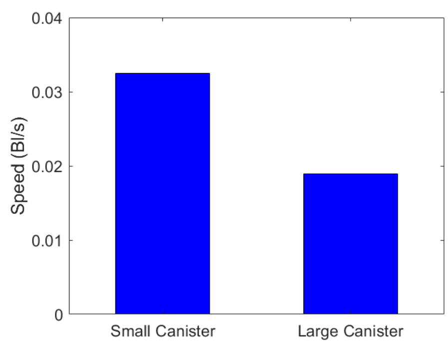

Figure S3: Comparison of the speed of the robot while carrying the small (left) and large (right) CO_2 canisters and regulators.

Consistency of pneumatic circuit oscillations

The soft ring oscillators produced continuous oscillatory signals with minimal control inputs.

To investigate the consistency of the periodic signal produced from the soft ring oscillator,

we measured the pressure in one of the leg chambers during 10 oscillatory cycles, and plotted them together vs. the time since the start of each oscillation (Figure S1). Over the oscillation period, the average standard deviation in the pressure between cycles was 9.4 kPa, with a worst case standard deviation of 15.5 kPa (19%) at $t = 1.8$ s.

Robustness of pneumatic circuit to pressure variations

To demonstrate the ability of our pneumatic CPG-based circuit to reject pressure disturbances (e.g. as would be caused by, for example, impacts with the environment during the gait), we tracked the position of the end of a soft leg during a normal oscillatory cycle and then we perturbed the input pressure to the pneumatic circuit, reducing it to atmospheric pressure for roughly one half-cycle. (The 3D movement of the foot was projected onto an XY-plane orthogonal to the leg in its resting position, as seen in Figure S2. The perturbation is labeled in blue on this figure.) The leg partially deflated and then the motion of the foot quickly returned to the pre-disturbance cycle. The red arrows on Figure S2 indicate the direction of motion of the foot.

Quadruped Robot Assembly

This section presents a step-by-step guide to design, fabricate, and assemble the quadruped robot. Please refer to Figure 1 to see the each component on the assembled robot. The fabrication and assembly process steps are as follows:

1. 3D Print Components
2. Leg Assembly
3. Quadruped Assembly
4. Valve Assembly

5. Sensor Assembly

1. **3D Print Components** The robot body, retaining rings, sensor boom, 3-2 valve mold, 4-2 valve mold, and sensor mold were 3D printed out of polylatic acid (PLA, Makerbot Replicator 2, Stratasys Inc.). We used a commercial multi-material 3D printer (Connex 3, Stratasys Inc.) to print the feet of the robot out of a soft material (TangoBlack+) for traction, as well as rigid back plates to mount the legs to the body of the robot (VeroClear). The foot assembly was composed of three parts: the soft treads, the center plate, and the connectors to the legs of the robot. The molds are composed of a three-part assembly and a cap. Two caps are fabricated for the 3-2 valve and 4-2 valve and one cap for the sensor mold. Each of the listed .stl files (Table S1) are available to download and print.

Object Name	Part	Assembly			
Robot Body	body_main.stl				
Sensor Boom	body_boom.stl				
Foot		foot_tread.stl	foot_plate.stl	foot_mount.stl	
Retaining Ring	leg_ring.stl				
Back Plate	leg_backplate.stl				
3-2 Valve Mold	3_2_mold_cap.stl	3_2_mold_bottom.stl	3_2_mold_excess.stl	3_2_mold_shell.stl	3_2_mold_top.stl
4-2 Valve Mold	4_2_mold_cap.stl	4_2_mold_bottom.stl	4_2_mold_excess.stl	4_2_mold_shell.stl	4_2_mold_top.stl
Sensor Mold	sen_mold_cap.stl	sen_mold_bottom.stl	sen_mold_excess.stl	sen_mold_shell.stl	sen_mold_top.stl

Table S1: List of .stl files

2. **Leg Assembly** The leg were composed of three parallel, connected chambers with bellows rotated 120 degrees about the longitudinal axis of the actuator. We used commercially-available plastic cylindrical bellows (Corr-A-Flex tubing, Teleflex Inc.) for the pneumatic chambers due to their extrinsic compliance (to allow bending) combined with the intrinsic stiffness of the material (to permit large internal pressures). 3D printed retaining rings held the three pneumatic chambers together. We slid three retaining rings over the three

chambers to fit into the grooves of the bellows. The back plates of the legs were tapped to attach threaded barbed adapters to the pneumatic lines. The three chambers were then press fit and glued onto the the feet and back plates.

3. **Quadruped Assembly** The legs of the quadruped are mounted on the body in the shape of an X for omnidirectional locomotion. The soft legs were mounted on a 3D printed rigid body frame. Each of the threaded adapters on the legs slide through the the three holes that are on the robot body with each foot oriented towards the ground. The base of each leg is then glued to the body of the robot.

4. **Valve Assembly** The 3-2 valve and 4-2 valve were composed of a cylindrical body, caps, and tubing. The body of the soft valves and caps were molded out of a soft polymer (MoldStar 30, Smooth-On Inc.). The polymer was poured into the cavity of the mold that form the cylindrical body of the valve. The polymer was also poured into the cap mold to form to the two caps of the valve. After the cylindrical body of the valve and the caps have cured, the opened/closed airways were fed through the holes in the caps. Each tube was connected to a barbed connector that contacts the membrane when the membrane switches state. we then used a silicone adhesive (SilPoxy) to adhere the caps to the cylindrical body. Tubes were fed through the side walls of the cylindrical body and the caps to create the inlet. The manufacturing process and assembly steps are similar for the 3-2 valve and the 4-2 valve except the 4-2 valve has twice the tubing routed through the caps.

5. **Sensor Assembly** The method used to manufacture the sensor is similar to the valves except there is only one cap. The fludic sensor channel is adhered to the cap of the sensor using a silicone adhesive (SilPoxy). Tubes were adhered to the side of the sensor to evacuate air bubbles in the sensor. The 3D printed sensor mount was press-fitted onto the

wall of the robot body and glued in place.

Considerations for future applications

This work presents an approach to the design of fluidic circuits that can be used to control a walking robotic toy. Since the circuits can be made completely out of molded or 3D printed polymers (rather than materials like metals and semi-conductors), we anticipate reduced materials costs. Furthermore, a single pneumatic source can be used to control multiple movements with simple pneumatic actuators, rather than requiring individual electromagnetic motors to control each behavior (e.g closing eyes, wiggling ears, and wagging tail would normally require a motor for each movement). Thus, this benefit increases with the complexity of the toy. The complexity of fabrication/assembly would also be reduced by combining the computation, sensing, and actuation components into a single fluidic system.

The soft fluidic valves can also be used in environments that do not allow metal such as in an MRI machine. Any metallic components can be placed outside of the MRI machine using a tethered version of the robot; the actuation and computation can be done in the MRI machine while the metallic pressure source used to operate the circuit can be moved to another location (it may also be possible to replace our metallic pressure vessel with an MRI-safe alternative).