SCIENCE ROBOTICS | FOCUS

SOFT ROBOTS

Pneumatic soft robots take a step toward autonomy

Anoop Rajappan, Barclay Jumet, Daniel J. Preston*

A four-legged soft robot walks, rotates, and reacts to environmental obstacles by incorporating a soft pneumatic control circuit.

Soft-bodied robots offer unique advantages in situations that require flexibility of form, resilience to damage, adaptability to rugged environments, and safety when interacting with humans (*1*). Looking to nature, animals such as octopuses, worms, and jellyfish accomplish complex feats of movement and locomotion using entirely soft body structures; after more than two decades of sustained research into mimicking these capabilities (*2*), the effort to create fully soft robotic systems has come to fruition in recent years (*3*). Nonetheless, fabricating viable sensors, actuators, control circuits, and power supplies from soft materials and unifying these components into a self-contained, responsive system remain key ongoing challenges facing roboticists (Fig. 1). Writing in *Science Robotics*, Drotman *et al.* (*4*) take an exciting step in this direction by successfully integrating soft legs with a soft pneumatic oscillator, powered by an onboard gas tank, to create a quadruped robot that walks without external assistance (Fig. 1). A secondary logic circuit, also pneumatic, modulates the robot's bioinspired gait pattern, enabling it to switch walking directions on demand or to reverse its direction automatically upon encountering physical obstacles detected by its integrated tactile sensor.

Complex motions involving multiple appendages, such as walking, impose a commensurate level of complexity on the control system needed to drive actuators in the sequences or patterns required for locomotion. Early soft robotic systems, even those actuated by fluidic pressure, therefore required electronic controllers and electromechanical valves to generate motion patterns and respond to sensory inputs (*1*). This approach relied on the use of rigid components, precluding the possibility of a fully compliant robot. A series of progressive developments—with origins tracing back to the Quake valve (*5*), and more recently evolving into soft implementations of microfluidic control (*3*, *6*), pneumatic valves (*7*), fluidic digital logic (*8*), and ring oscillators (*9*) for robotic systems—have since permitted a gradual transition away from hard electronic controllers to fully soft and entirely fluid-driven logic circuits. Drotman and colleagues improve upon an earlier pneumatic valve design (*7*) and introduce a bistable pneumatic latch, which operates as a soft memory bit to store the robot's direction of travel. Careful optimization of the control architecture allowed them to minimize the number of valves and actuators needed, thereby reducing weight, system complexity, and failure points.

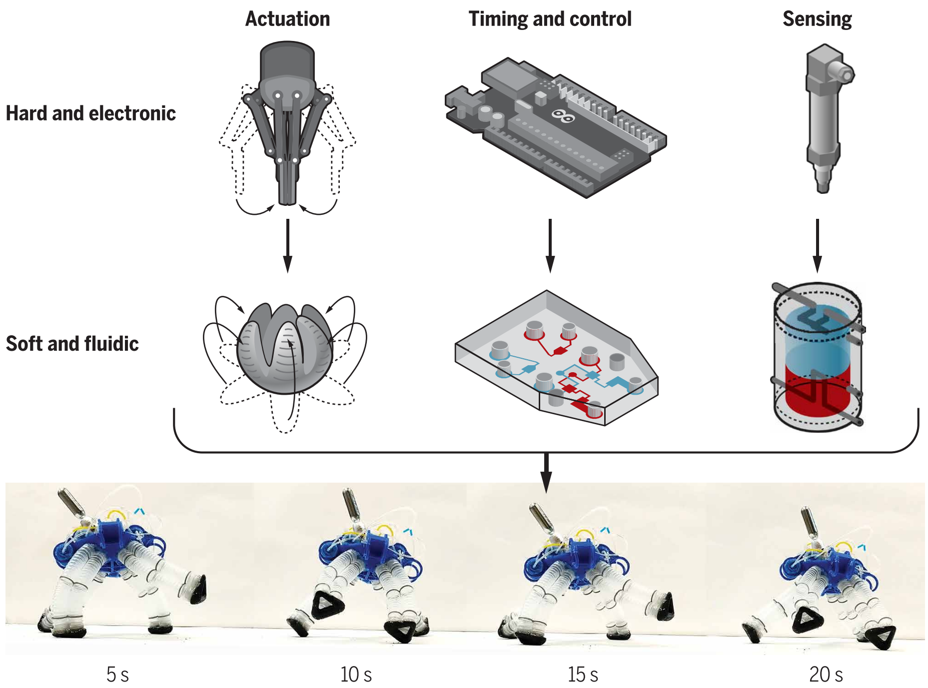

Fig. 1. The evolution of soft robots from their traditional rigid counterparts. Rigid, electrical components in conventional robots—actuators, control circuits, and sensors—are replaced by soft, fluidic analogs. The integration of these fluidic components creates a soft robot that can function independently. For example, guided by internal fluidic logic, soft robots are now able to perform tasks such as walking and avoiding obstacles without external input or assistance.

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In building their walking robot, Drotman *et al.*, like other researchers before them, draw inspiration from central pattern generators (or CPGs) found in nature. CPGs are neuronal circuits that function as biological oscillators; these oscillators generate periodic nerve impulses, which many animals utilize to drive the subconscious rhythmic muscle contractions involved in walking, flying, swimming, and breathing (*10*). Analogous fluidic oscillators can be used to drive rhythmic actuation of end effectors in soft robots. For example, a soft ring oscillator composed of three pneumatic inverters connected in a circular loop (*9*) produces pressure pulses of a fixed frequency when supplied with a source of compressed gas (e.g., from a disposable gas canister). Drotman *et al.* use this periodic signal to cyclically inflate and deflate the three chambers in each of their robot's four legs, causing them to flex synchronously in diagonal pairs; the order and timing of actuation is tuned using additional pneumatic valves to

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change the robot's walking speed and direction. The resulting walk mimics the diagonal gait pattern observed in turtles, lizards, and other animals with sprawling limbs (Fig. 1). By emulating nature, researchers may leverage the versatility of soft oscillators coupled with soft logic elements in the future to allow soft robots to perform more complex repetitive motions than walking—for example, picking, placing, and sorting. Going a step further, we envision these circuits enabling a new generation of fully soft robots with onboard memory and decision-making capabilities.

Even in light of the notable contribution by Drotman and co-workers, several overarching challenges still beset the field of soft robotics. Future efforts must focus on developing additional fully soft components, in particular power supply units, to enable untethered operation without compromising the compliance of the robot's body and its attendant benefits. As in the case of CPGs, we may look to nature again for inspiration and answers; for example, the exothermic decomposition of a liquid monopropellant, as occurs in the abdominal glands of the bombardier beetle, has been successfully adapted as a chemical energy source for powering soft robots (*3*). Concurrently, to scale up from prototypes to serviceable designs, soft fabrication processes must be evolved and fine-tuned until soft logic components can be mass-produced repeatably and cost-effectively at sizes appropriate for actuation of useful soft devices. In this regard, recent advances in 3D printing of elastomers show considerable promise in creating complex geometric structures from soft materials. Ultimately, while roboticists have covered impressive ground in recent times, soft robots with pneumatic brains have several exciting miles left to tread on the road to full autonomy.

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