ACTUATORS

Electronics-free soft robot has a nice ring to it

Kristen L. Dorsey

A fluidic ring oscillator provides timing to soft robots, thus enabling complex locomotion and load carrying.

Mechanical compliance, robustness, and continuum deformation are integral properties and advantages of soft robots. Over the past 2 years, key components to improve soft robot autonomy—fluidic timing and logic—have been integrated into such robots, with exciting advances over earlier capabilities. Many soft robots use changes in fluid (e.g., air) pressure to deform one or multiple actuators and induce crawling, walking, rolling, or climbing (*1*–*5*). A previous limitation of this actuation approach was the lack of circuits to source changes in fluid pressure; earlier works typically relied on preprogrammed sequences, external electronics, or operator control to achieve motion. To become fully autonomous and maintain their mechanical advantages, fluidically actuated robots will need soft sensors, actuators, and circuits that can fully control and complete actions.

Writing in *Science Robotics*, Lee *et al.* (*5*) address the challenge of timing in soft robots through their buckling-sheet ring oscillator (BRO), a soft robot that couples fluid pressure control across three components or "sheets." Each sheet is an inflatable bladder with a fluidic input and output and connections to high- and low-pressure fluids. The operation of the fluidic circuit is analogous to an electronic ring oscillator. The first sheet within the BRO expands when a high-pressure fluid is applied to its input. The expansion buckles the sheet and closes off the connection to the neighboring sheet's high-pressure fluid input. The second sheet deflates, opening a high-pressure connection to the third sheet, which expands. Because the three sheets are coupled in a ring, the fluid pressure oscillates, and each sheet expands and deflates with regular timing. Each sheet, when inflated, mechanically buckles and deforms. Lee and co-workers exploit this deformation to achieve crawling, climbing, and swimming motions using only a high-pressure fluid source and an environmental pressure.

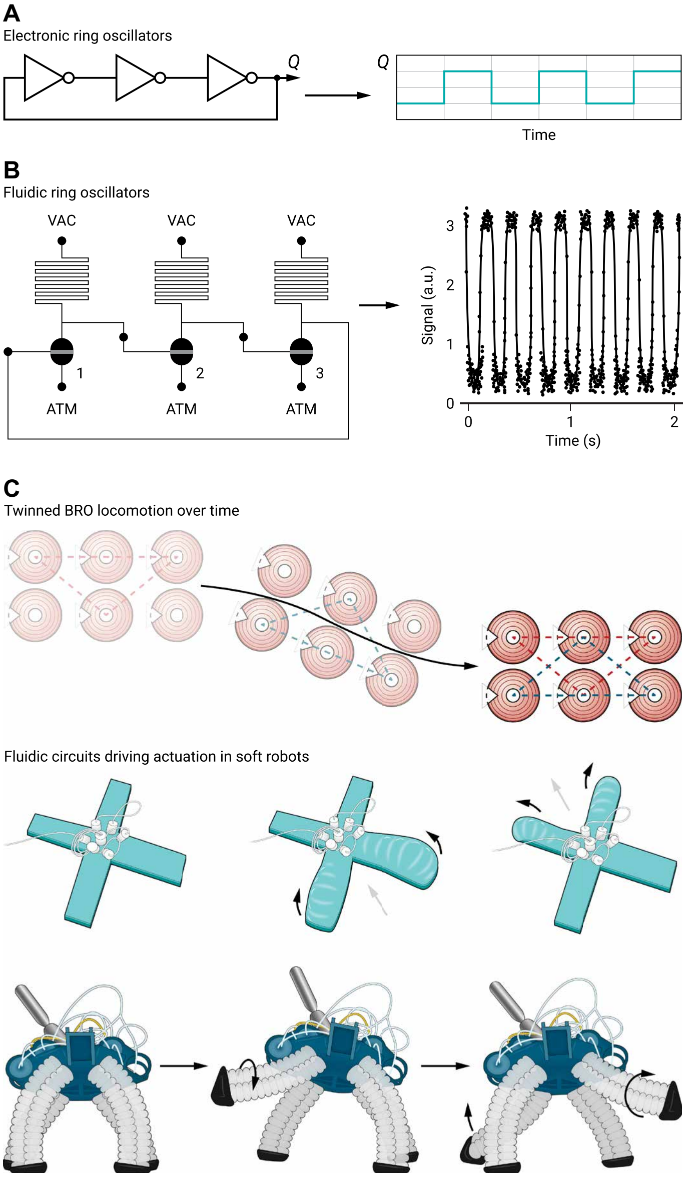

Fig. 1. Development of fluidic ring oscillators for soft robot locomotion. Fluidic timing circuits are inspired by (**A**) electronic logic, particularly ring oscillators. (**B**) Early fluidic circuits (*7*), used for microfluidic applications, demonstrated key principles for electronics-free fluidic actuation. (**C**) Work in the past 2 years has demonstrated fluidic timing using viscous delays (*1*), fluidic circuits (*2*), and fluidic ring oscillators (*5*) to generate locomotion without electronics.

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The fluidic timing approach used by Lee and colleagues builds on earlier fluid circuits inspired by CMOS logic and timing (Fig. 1). Notable examples include elastomeric valves that operated like diodes or transistors (*6*) and pneumatic inverters coupled into ring oscillators (*7*) (Fig. 1). These components and circuits were envisioned for timing in microfluidic circuits, but the working principles were soon applied in soft robots to fluidic digital logic gates for grasping (*8*), artificial finger articulation (*9*), and a range of locomotion strategies (Fig. 1) (*1*–*5*). Upon receiving a single pulsed pressure, a soft robot crawled by prescribing the delay in the fluid flow between actuators (*1*). Although this approach reduced the number of valves for locomotion, it still required a pulsed pressure from an external source. Recently demonstrated fluidic delay circuits, valves, and fluidic oscillators have produced robots that can roll like balls (*3*), climb the inside of

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pipes (*4*), and even mimic the gait of turtles (*2*).

In contrast to other soft robots with fluidic circuits, the BRO embeds a ring oscillator circuit within each actuator. The deformation of each sheet directly controls the oscillator operation, which reduces valves and fabrication complexity. The BRO motion is set through its structure—a BRO with sheets oriented with the buckle location parallel to one another will move forward, whereas one with angled sheets will rotate. The twinned BRO, a set of two mechanically coupled, fluidically decoupled BROs, is also able to rotate or translate by selecting which set of BROs receives a pressurized fluid. With the aid of a micropump, the BRO may operate untethered in air, as well as under water using an external pressure source. In air, the robot can also carry loads up to four times its weight.

The BRO and its fluidic oscillators hold promise for the future of autonomous soft robots. Although an external signal is currently required to switch the twinned BRO from forward to either turning motion, future controllers could use elastomeric sensors or other logic to select which BROs are active. The locomotion rate is ~10 mm/s, which the authors envision scaling to meter-sized robots with an ensuing increase in speed to over 10 m/min. Last, sources of pressurized fluid are required, mandating either a tethered connection, an on-board pump, or a chemically generated pressure source. The single and twinned BROs are an important step toward controllable and mechanically soft robots that can operate out in the world.

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