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DOI
10.1126/scirobotics.adw7660

Publication date
2025

Document Version
Final published version

Published in
Science Robotics

SOFT ROBOTS

Physical control: A new avenue to achieve intelligence in soft robotics

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Physical control embodies motion intelligence in soft robots via self-regulating oscillations, sequences, and reactions.

Robots thrive in industry, but they struggle outside structured environments, because incremental improvements in their performance are driven by data-hungry algorithms at the cost of disproportionate increases in computational power. Despite advancements in artificial intelligence, robots still lag behind biological organisms, which move efficiently in complex environments, relying on nervous systems that use a fraction of the computational power of current robots.

One fundamental limitation is the reliance on digital computation—which is appropriate for high-level reasoning but is not the natural language of motion generation. Nature offers a solution: Living beings generate intelligent motions by leveraging the nonlinear and dynamic properties of their bodies and their interactions with the environment, a concept known as embodied intelligence (*1*). These biological insights have fueled researchers to rethink the concept of what a robot is, resulting in the emergence of soft robots, mechanical systems made of soft materials akin to biological tissues. As part of this new wave, we identify the concept of physical control as the emerging trend of embedding control capabilities directly into the robot's physical structure instead of using software and microcontrollers.

Here, we focus on physical nonlinearities embodied in soft materials, such as snap-through instabilities, rate dependencies, and light responsiveness, and how these mechanisms enable physical control, regulating sensorimotor actions without microcontrollers. Using recent examples that demonstrate physical control in soft robotics, we highlight three fundamental types of self-regulating behavior that we classify into oscillation, sequence, and reaction.

Self-oscillation is the spontaneous generation of rhythmic outputs from a constant input, as seen in biological systems, from heartbeats to neural circuits (central pattern generators) governing locomotion. In robotics, oscillations are programmed via software, but soft materials can generate them mechanically because of their nonlinear properties.

Researchers have developed a soft oscillator by introducing slits into a snap-through membrane with a highly nonlinear pressure-volume relationship. When subjected to a constant volume flow and operating below the pressure peak, the slits remain closed, allowing pressure to build up. At the pressure peak, an instability everts the membrane and opens the slits, releasing pressure and triggering a resetting snap-back that restarts the cycle (Fig. 1A) (*2*). In an alternative design, snap-through membranes are used to kink tubes to block the flow and create bistable soft valves (*3*). Such valves, when combined in odd numbers, give rise to ring oscillators where one valve state influences the next.

Furthermore, physical control can coordinate a sequence of movements using minimal inputs. Traditional robots require separate control inputs for each degree of freedom, but soft robots can exploit physical properties to generate sequential actuation from only a single input. Analogously, biological systems rely on muscle synergies to recruit muscle groups via a single neural command. This strategy was used to play a robotic piano with a single pressure input (*4*) using inflatable conical shell actuators that pop from a convex to concave shape to press the piano keys. By designing these actuators to pop at different pressures, a sequence of notes is played as the input pressure is modulated between these snapping thresholds (Fig. 1B). Alternatively, inserting dissipative elements in the actuator networks allows for controlled delays, enabling soft robots to crawl via traveling pressure waves (*5*).

Last, adaptive behavior in biological systems entails the ability to react to changes in the environment through feedback. In robots, reactive intelligence is traditionally implemented via sensor-microcontroller-actuator loops, but soft robots can close this loop physically. Two classes of reactions exist: Boolean (discrete) and analog. Boolean responses operate through logic gates, triggering predefined actions under specific conditions. In nature, the Venus flytrap, a carnivorous plant that preys on insects, exhibits a similar Boolean response: It only snaps shut when sensory hairs are touched in a specific pattern. In soft robotics, fluidic logic gates process fluidic signals using networks of bistable soft valves to physically implement any Boolean function (*6*). For example, a single bistable valve can function as a NOT gate, converting a low-pressure input into a high-pressure output. A recent example harnessing soft Boolean logic is a turtle-inspired robot that changes its path using bistable fluidic touch sensors. When the robot collides with an obstacle, the sensor switches states, altering the input of the logic circuit that controls its direction (Fig. 1C) (*7*). Regarding analog reactions, nature again is a source of inspiration, given that most self-regulating mechanisms in nature are continuous. Functional soft materials, which deform in response to stimuli like light or heat, offer an avenue to autonomously adjust stiffness or shape. Examples include phototactic systems that harness the presence of light to locally stiffen parts of the body and steer the robot toward a light source (*8*).

Oscillation, sequence, and reaction have the potential to form more complex physical control systems when interconnected. Oscillatory motion may drive sequencing, whereas

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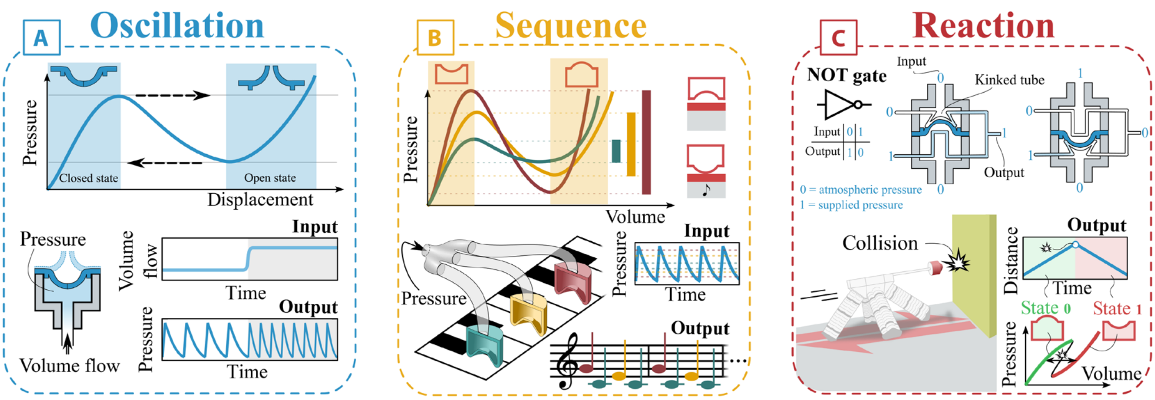

Fig. 1. Self-regulating oscillation, sequence, and reaction as fundamental features of physical control. (**A**) Oscillation. In a fluidic relaxation oscillator, a single steady input is converted into a periodic oscillation, harnessing the unique characteristics of a snap-through membrane with slits (*2*). The membrane snaps between two states when the pressure exceeds a peak or valley threshold. In one state, the slits remain closed (pressure builds up, no volume flow), and in the other, they open (pressure is released, allowing high-volume flow). When the membrane is loaded by a constant volume flow, a spontaneous oscillation emerges, with a frequency that is linked to the magnitude of the volume flow. (**B**) Sequence. A single modulated input generates a discrete sequence of multiple outputs, harnessing the snapping characteristics of conical shells. By interconnecting multiple fluidic snapping actuators, with different snapping pressures, to the same pressure input, a robotic system can play a melody on a piano by simply modulating the input pressure between snapping thresholds (*4*). (**C**) Reaction. Boolean logic is implemented in soft robots using soft bistable valves and realized using snapping membranes that kink tubes to block volume flow (*3*), functioning as NOT gates. The integration of bistable sensing elements in Boolean fluidic circuits makes soft robots responsive to their environment, switching trajectories when colliding with a wall (*7*).

reactions may modify oscillations or sequences on the basis of external stimuli that vary stiffness or shapes. This interdependence mirrors biological systems, where rhythmic motion, like walking, adapts on the basis of sensory feedback.

Despite its promise, physical control faces several challenges that prevent current soft robots from reaching living systems' capabilities. First, physical control lacks a unifying modeling framework (*9*). Developing such a theory requires merging hybrid systems theory (which describes both continuous and discrete behaviors) with energy-based models like bond graph theory, which expresses the behavior of dynamic systems in terms of generalized effort and flow variables. Moreover, current physical control systems rely on empirical methods, limiting their complexity. Achieving advanced behaviors requires a systematic inverse design strategy. This approach must integrate physics-informed computational tools to generate robot architectures based on desired behaviors. Although inverse design has been applied to single nonlinear features, designing multicomponent nonlinear systems remains an open challenge. Last, biological intelligence operates across multiple lengths and timescales: Micrometer-sized neurons rapidly spike to control the slow movements of macroscopic limbs. Soft robots must similarly integrate physical control at different scales to achieve complex, adaptive behaviors. Multimaterial, multiscale additive manufacturing will be key to building robots that combine low-level physical control with high-level cognitive control. If successful, physical control will open up exciting possibilities to bridge the gap between biology and machines and realize the moonshot goal of soft robotics: autonomous materials systems that move, adapt, and interact as seamlessly as living beings (*10*).

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Acknowledgments: We thank the following research supporters: the German Research Foundation (DFG, EXC-2193/1-390951807), the European Research Council (ERC, ILUMIS 101076036 and RIPLEY 101165078), and the Volkswagen Foundation (9D761).

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