

# Interlocking-based multistable actuators as fluidic memristors

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## Abstract

This work introduces neurofluidic systems as a strategy to enable embodied intelligence in soft robots without reliance on conventional electronics. Central to this approach is a memristive fluidic actuator (MFA), a soft, pressure-driven component that integrates actuation, fluidic resistance and memory within a single structure. The MFA operates via a single pressure input–output port and exhibits multistate, nonvolatile resistance behavior, enabling its use as a tunable analog weight in fluidic networks. The MFA consists of a soft inflatable chamber driving the position of the internal pin valve. The multistable mechanism is introduced by attaching a jigsaw-inspired interlocking mechanism to the soft actuator. We also demonstrate control of three distinct behaviors of a dome-shaped snapping actuator that is enabled by a memristive fluidic actuator (MFA), switching between no motion, reciprocal motion and nonreciprocal motion.

## 1 Introduction

Soft robotics has made notable progress in achieving compliant, bio-inspired motion and sensing [1, 2, 3]. Despite these advances, the implementation of control and decision-making in such systems remains largely externalized, typically relying on rigid electronics or simplified fluidic logic elements [4, 5, 6]. This separation between body and control limits the ability of soft robots to fully exploit their inherent adaptability, particularly in complex or unpredictable environments.

A growing research direction seeks to address this gap by embedding functional intelligence directly into the physical substrate of the robot [7]. Rather than treating control as a separate layer, this approach leverages material properties and structural design to enable distributed, adaptive behavior. Fluidic systems, in particular, offer a promising platform for such integration, as they naturally couple mechanical response with signal transmission.

Physical controllers in soft robotics commonly include self-oscillators and sequencers, each enabling distinct forms of autonomous behavior [7]. Self-oscillators convert a constant input into periodic outputs, often through relaxation mechanisms that switch between discrete states based on output-dependent thresholds. For example, bistable soft valves leveraging the hysteretic response of snapping hyperelastic domes, combined with the kinking of flexible tubes, have been used to generate autonomous oscillations [8]. An entirely 3D-printed version of the valves has been used to implement a ring oscillator that controls the walking gait of turtle-like robot [9]. Other self-oscillators have been introduced in soft robotics, inspired by the ketchup valve design [10] or the "dancing" inflatable tube [11]. In a related study, the bistable memory and sensing elements with a ketchup valve design self-oscillator are implemented in a crawling soft robot and hence various crawling behaviors are achieved [12].

On the other hand, sequencers are designed to produce discrete, ordered patterns of actuation required for tasks such as locomotion or object manipulation [13]. However, implementing complex sequences typically demands multiple control signals and additional fluidic components, increasing system complexity, weight, and cost in soft robotic platforms. A study on nonlinear fluid flow networks also introduced the concept of the fluidic memristor, a soft fluidic element capable of exhibiting history-dependent resistance and hysteresis behavior [14]. Such systems have been explored for applications in soft robotics, where tunable fluidic resistance can enable adaptive control and memory-like functions in soft actuators and fluid-driven devices. These findings also provide insight into biological vascular networks and other soft material systems with nonlinear flow behavior. Furthermore, flexible memristors and systems have been explored for bio-inspired neuromorphic computing in soft robotics; however, this approach still relies on electronic components, whereas fully electronics-free soft robots remain an important goal [15]. In this context, we introduce a memristive fluidic actuator (MFA) as a core element of neurofluidic systems. Unlike existing fluidic controllers that rely on discrete components, the MFA integrates actuation, fluidic resistance, and memory within a single soft, pressure-driven structure. Through its multistate resistance behavior, it enables modulation of pressure and flow, allowing it also to function as a tunable analog weight in a fluidic network. This provides a scalable approach toward adaptive, electronics-free control in soft robotic systems.

## 2 Design and Fabrication

### 2.1 Memristive fluidic actuator

The memristive fluidic actuator is made of a Smooth-Sil 936 silicone-based inflatable actuator that incorporates an

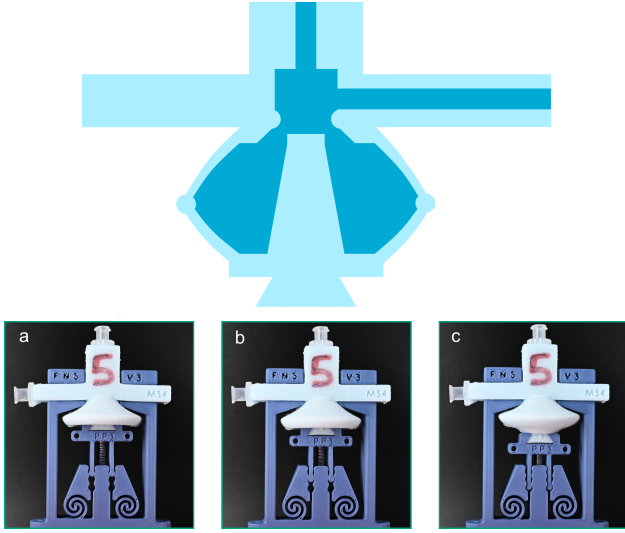


**Figure 1** Cross-sectional view of the silicone actuator shows the internal pin valve that modulates the fluidic channel and hence fluidic resistance. Below: working principle of memory and resistance with (a) high, (b) medium, and (c) low resistance states.

internal pin valve and a progressively constricted fluidic channel. The silicone actuator is casted in a single step using 3D-printed molds (Fiberon PPS-CF10) and a 3D-printed sacrificial core (BVOH). The silicone actuator is then housed within a PLA frame (**Figure 1**). The internal pin is mechanically stabilized by a jigsaw-inspired interlocking structure integrated into the frame, enabling discrete and repeatable configurations that correspond to multiple fluidic resistance states [16].

State transitions are governed by a compliant double-spiral hinge mechanism, which constrains the motion of the pin and permits switching only when the applied pressure exceeds predefined thresholds [17]. This threshold-dependent behavior ensures stable retention of each resistance state under subcritical conditions. In addition, a spring element positioned between the pin and the frame facilitates reversible operation, allowing smooth transitions from low to high resistance states under vacuum actuation. The geometry of the interlocking features, the thickness of the double-spiral hinge, and the spring characteristics are carefully tuned to balance multi-stability, switching thresholds, and actuation performance. Together, these design elements enable controlled, repeatable state changes while maintaining reliable fluidic resistive memory within the fluidic system.

## 2.2 Asymmetric snapping actuator

To demonstrate the capabilities of the MFA, an asymmetric snapping actuator is used as a test platform (**Figure 2**). Fabricated from Smooth-Sil 950 silicone, the actuator features an eccentric dome geometry that induces controlled, directional deformation, as described in [18]. The offset design ensures that deformation initiates on one side and propagates across the structure during pressurization, with the sequence reversing upon depressurization. This results

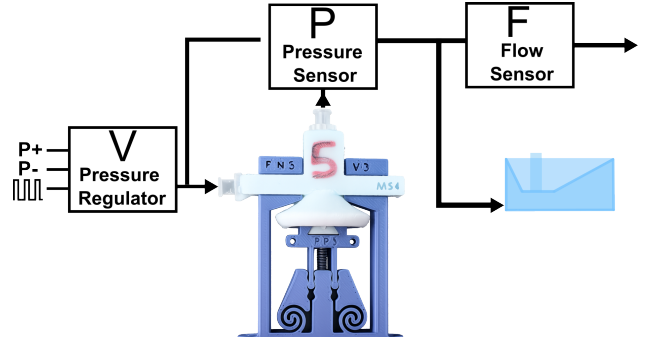


**Figure 2** Experimental setup showing pressure regulator valve (V), pressure sensor (P), flow sensor (F), MFA, and asymmetric snapping actuator.

in a repeatable asymmetric motion cycle capable of producing diverse actuation behaviors. Varying the pressure amplitude or frequency of actuation results in dynamic behavior of the snapping cycle [18].

## 3 Experimental Setup

The control signal is generated using a Keysight 33600A Series Waveform Generator and applied to a pressure regulator valve connected to in-house positive and negative pressure supplies (**Figure 2**). The input signal consists of repeated sequences of five low-amplitude pulses alternating between 1 s at 0.049 bar and 1 s at a baseline level of 0 bar. The oscillatory pulse sequence is employed to drive the asymmetric snapping actuator mechanism within its subcritical regime and to characterize its dynamic response for each resistance state (**Figure 3**).

Between these pulse sequences, isolated higher-amplitude pressure spikes (e.g., 0.096 bar and 0.224 bar) are applied. These spikes, which exceed the respective switching thresholds of the resistance states, are used to induce transitions from the high to low resistance state. Between excitation segments, the signal returns to baseline to maintain the current state. The flow rate downstream of the MFA is measured using a Honeywell AWM5102VN flow sensor, while the pressure difference across the MFA is measured using a Honeywell 015PDAA5 differential pressure sensor, with all measurements recorded using a National Instruments DAQ system.

## 4 Results and Discussion

The results demonstrate that the MFA exhibits multistate resistance behavior governed by the applied pressure, with stable state retention. As the fluidic channel gap within the MFA progressively decreases, two key outcomes emerge. First, a distinct pressure drop across the MFA is observed for each resistance state (**Figure 3**). In the high-resistance state (a), the pressure difference is close to the control pressure. In the medium-resistance state (b), the pressure difference is approximately half of the control pressure, while in the low-resistance state (c), it becomes nearly zero. Consequently, for a constant control pressure of 0.049 bar,

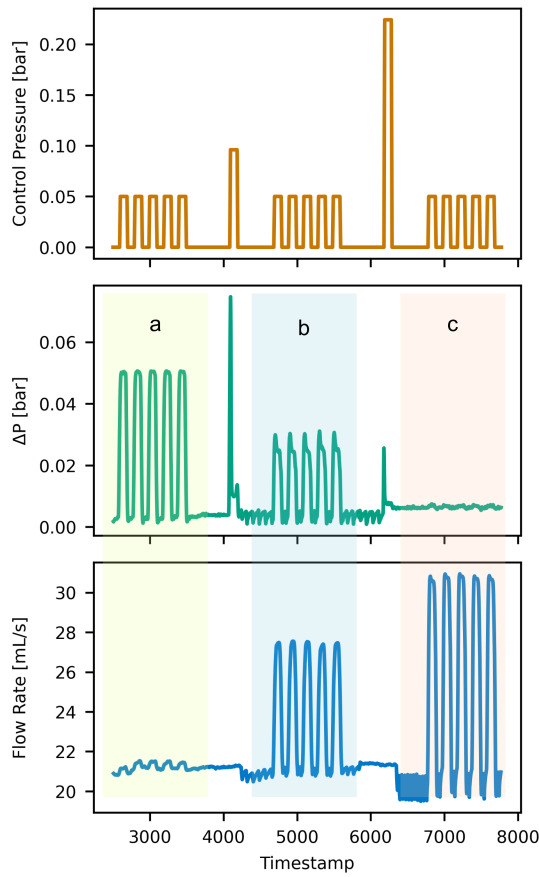


**Figure 3** Control pressure input and corresponding MFA response: pressure difference and flow rate across resistance states (a) high, (b) medium, and (c) low.

three distinct output pressure levels can be achieved. Second, analogous to an electrical circuit, variations in resistance lead to corresponding changes in flow rate. The measured flow rates clearly follow the defined resistance states, as shown in the plots (**Figure 3**). This behavior highlights the potential of these discrete resistance states to function as tunable weights within a neurofluidic circuit. Building on this multistate behavior, the snapping actuator directly translates the discrete pressure outputs of the MFA into distinct responses (**Figure 4**). As the effective pressure delivered to the actuator varies across resistance states, a corresponding shift in deformation dynamics emerges. Considering that the actuator undergoes a snap-through transition at approximately 0.041 bar, these pressure levels determine whether the system remains below or crosses the instability threshold [18]. Accordingly, the asymmetric



**Figure 4** Asymmetric snapping actuator trajectories: (a) high resistance—no motion, (b) medium—reciprocal, (c) low—nonreciprocal

snapping actuator remains inactive in the high-resistance state (a). In the medium-resistance state (b), where the applied pressure is close to but below the snapping threshold, the deformation remains smooth and reversible, resulting in reciprocal trajectories under cyclic actuation. In contrast, in the low-resistance state (c), the higher effective pressure drives the actuator beyond the instability point, leading to nonreciprocal behavior characterized by asymmetric loading and unloading paths. Trajectory tracking implemented in Python further confirms this distinction, showing overlapping cycles in the mid-resistance regime and pronounced hysteresis in the low-resistance regime. Together, these results demonstrate how the MFA not only modulates pressure levels but also governs the transition between reciprocal and nonreciprocal actuation, which can be leveraged to emulate different locomotion strategies in soft robotic systems [18].

## 5 Conclusion

This work demonstrates that a memristive fluidic actuator can reliably encode and retain multiple resistance states, enabling direct modulation of pressure and flow within a soft system. These states produce three distinct pressure differences and corresponding flow rates, which in turn control the behavior of an asymmetric snapping actuator. As a result, the actuator exhibits three regimes: no actuation, reciprocal motion, and nonreciprocal dynamics. Future work will focus on combining multiple MFAs together to build a neuro-inspired fluidic network, which is capable to perform complex computation and adapt to dynamic inputs. Such integration provides a pathway toward adaptive and fully embodied control architectures, with potential applications in soft robotic locomotion.

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## 6 Literature

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