FlexEOP: Flexible Shape-changing Actuator using Embedded Electroosmotic Pumps

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ABSTRACT

Shape-changing actuators have been widely explored in the field of human-computer interaction (HCI), enabling various applications of shape-changing interfaces across from haptic feedback devices to robotics. However it is still challenging for existing methods to build shape-changing actuators that are flexible, capable of complex shape-changing behaviors, and highly self-contained at the same time. In this paper, we proposed FlexEOP, a method to create flexible electroosmotic pumps that are fully composed of flexible materials, facilitating shape-changing actuators with high flexibility and self-containment. We introduced the structure of FlexEOP and then demonstrated the design space of FlexEOP, including shape-changing display on flexible strips, panels, and curved surfaces, and a novel design of soft robotic fiber. Based on FlexEOP, we envision future applications including wearable tactile devices, curved shape-changing displays, and multi-degree-of-freedom self-contained soft robotics.

CCS CONCEPTS

• **Human-centered computing** → *Interactive systems and tools*; **Haptic devices**; **Interactive systems and tools**; • **Hardware** → **Sensors and actuators**; **Emerging interfaces**; **Tactile and hand-based interfaces**; *Electromechanical systems.*

KEYWORDS

Shape-changing Actuators, Shape-changing Display, Haptics, Soft robotics, Fluidics, Electroosmotic pump, Programmable Materials

ACM Reference Format:
Tianyu Yu, Yang Liu, Yujia Liu, Qiuyu Lu, Teng Han, and Haipeng Mi. 2018. FlexEOP: Flexible Shape-changing Actuator using Embedded Electroosmotic Pumps. In *Proceedings of Make sure to enter the correct conference title from your rights confirmation emai (Conference acronym 'XX).* ACM, New York, NY, USA, 5 pages. https://doi.org/XXXXXXX.XXXXXXX

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Conference acronym 'XX, June 03–05, 2018, Woodstock, NY

ACM ISBN 978-1-4503-XXXX-X/18/06
https://doi.org/XXXXXXX.XXXXXXX

1 INTRODUCTION

Shape-changing actuators have been widely explored in the field of human-computer interaction (HCI), enabling various applications of shape-changing interfaces, such as shape-changing display [8], haptic feedback devices [25], and robotic interfaces [4].

A major category of shape-changing actuators is built on electromechanical actuators, which typically used electrical, magnetic, and mechanical components, providing powerful and well-engineered shape-changing performance [8, 17, 29]. However, they still face the challenges of cumbersome hardware, large volume consumption, and working noise. To address these limitations, researchers in recent years have begun to explore material-based shape-changing actuators, which are lightweight, flexible, and quiet, offering the opportunity to be embedded into objects in a more seamless manner [2, 5, 13].

One method is to utilize shape-changing materials that perform reversible shape changes in response to physical environments, such as Shape Memory Alloy (SMA) [10], Liquid Crystal Elastomer [5], and Low Boiling-point Liquid [18], which deform according to temperature, or hydrogels [14], paper [26], and bio-materials [21, 28] that deform according to moisture. However, due to the difficulty in precisely controlling the physical inputs (e.g., temperature and moisture), it is challenging to design complex and accurate shape-changing behaviors with these materials.

Another method employs pneumatic shape-changing materials, often flexible and lightweight, capable of exerting significant force and forming complex shapes when pressurized [9, 12, 19, 27]. However, bulky hardware such as pumps and valves remains necessary, especially in the presence of multiple independent actuators [6, 7].

Recently, electro-actuated materials have received wide attention for their highly dynamic physical properties, such as shape, in response to electrical stimuli [11]. Electrical hydraulic actuators are one technique that uses electric fields to drive liquid movement and output shape-changing behaviors [16, 20, 22]. Since the shape changes are actuated by incompressible liquid and avoid using electromechanical components, these actuators generally offer both high self-containment and mechanical performance at the same time [25].

Our research is based on electroosmotic pumps (EOPs), a technique to create electrical hydraulic actuators characterized by lower operating voltages and more compact form factors. Building on previous work that has demonstrated how to embed EOPs into shape-changing displays [25] and miniature haptic displays [23], we proposed FlexEOP, a method to create flexible EOPs that are fully composed of flexible materials to facilitate flexible shape-changing actuators. We introduced the structure of FlexEOP and then demonstrated the design space of FlexEOP, including shape-changing display on flexible strips, panels, and curved surfaces, and a novel design of soft robotic fiber. Based on FlexEOP, we envision future applications including wearable tactile devices, curved shape-changing displays, and multi-degree-of-freedom self-contained soft robotics.

2 FLEXEOP STRUCTURE

We use the term "Shape-changing unit" to refer to one EOP that can actuate shape-changing effect independently. The shape-changing unit is built on the basic structure of embedded EOPs from previous work [25] and shares a similar working mechanism. However, we have implemented significant modifications to facilitate the flexibility of the actuators, which includes the following parts (Figure 1a):

Reservoir. The top and bottom layers consist of flexible silicone reservoirs that seal the pumping fluid and output shape changes driven by the internal fluidic movement. We used Smooth-on Ecoflex 00-30 silicone and 3D-printed molds to fabricate the reservoirs. We proposed two reservoir designs that can perform vertical and horizontal expansion respectively:

- *Vertical expansion:* This reservoir is fully connected inside, and the outside is sealed by a 0.5mm silicone membrane at the top. When the liquid flows in, the top membrane expands vertically, producing a protrusion deformation (Figure 1b).
- *Horizontal expansion:* This reservoir includes partitions perpendicular to the electrode direction, similar to the typical pneu-net architecture applied in soft robot design [24]. When the liquid flows in, the reservoir expands horizontally, causing the entire material to bend towards the opposite side (Figure 1c).

Flexible printed circuit (FPC). We used FPC to fabricate the electrodes of the EOPs, which significantly decreases the thickness of the EOPs and enhances the flexibility of the actuator. Each pair of an upper and a lower FPC electrode applies an electric field to actuate the internal electroosmotic flow. The diameter and pitch of the vias on the electrode refer to [25].

Pressure-sensitive adhesive (PSA). We used 3M468MP double-sided PSA to bond the structural layers. Notably, we replaced the original PET spacer in the EOP in previous work [23, 25] with a 0.4mm-thickness PSA layer. This modification significantly enhances the flexibility of the actuator due to the remarkable stretchability of PSA, while providing insulation and adhesion at the same time.

Pump membranes and pumping fluid. Similar to the [25], we used glass fiber filter as the the pump membranes, used propylene carbonate as the pumping fluid.

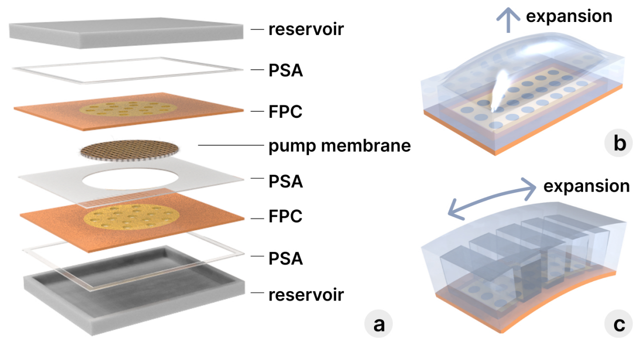

Figure 1: (a)FlexEOP structure. (b-c)Reservoir with vertical and horizontal expansion. Omit the reservoir on the other side.

To actuate and control the shape changes of the shape-changing units, we used a DC converter to provide a 250V voltage source, and used a series of relays controlled by an Arduino board to apply -250V, 0V, or +250V voltage on each pair of the electrodes. The pumping fluid moves in opposite directions under positive or negative voltage. The changes of the fluidic distribution cause the deformation of the entire flexible composites, functioning as a shape-changing actuator.

3 FLEXEOP DESIGN SPACE

In this section, we demonstrate the design space of FlexEOP, including shape-changing display on strips, panels, and curved surfaces, and a novel design of soft robotic fiber.

Strip shape-changing display. We arranged the shape-changing units in a linear sequence on a strip to create one-dimensional flexible pixel-based shape-changing display. Figure 2 shows a strip with 9 shape-changing units in array, where each shape-changing unit is 10x10mm in size and capable of independently protruding or recovering. The flexible strip can conform to the curved surfaces of the human body or objects through bending. For example, it can be wrapped around a person's wrist as a wearable tactile feedback bracelet, or adhered to the surface of an object to alter its outline.

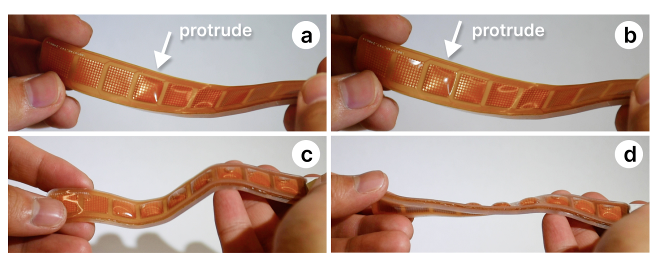

Figure 2: A flexible strip shape-changing display with 9 shape-changing units in sequence.

Panel shape-changing display. We arranged the shape-changing units in a matrix configuration on a panel to create a two-dimensional flexible pixel-based shape-changing display. Figure 3 shows a panel with a 3x3 arrangement of shape-changing units, each sized 10x10mm.

This flexible panel can be adhered to human skin, providing rich tactile feedback. Figure 4 shows a Braille display panel of two Braille characters. The panel is composed of miniature round-shaped shape-changing units, each with a diameter of 1.6mm and a pitch of 2.5mm. This flexible panel demonstrate the potential to be embedded into soft wearables, enabling dynamic Braille display with good comfort.

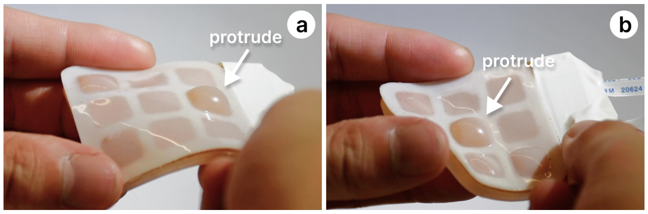

Figure 3: A flexible panel shape-changing display with shape-changing units in a 3x3 matrix.

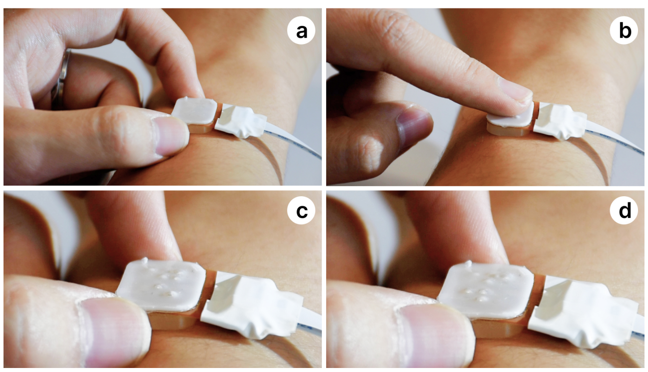

Figure 4: A flexible Braille display composed of miniature round-shaped shape-changing units.

Shape-changing display on curved surfaces. Figure 5 shows a planar actuator composed of three line-shaped shape-changing units embedded into the surface of a curved shell. Each unit can independently protrude or recover, rendering a wave-like shape- or texture-changing animation on the curved surface through the coordination of the shape-changing units. This design can be applied to various scenarios for rich visual and tactile information display, such as data physicalization [1], education [15], remote communication [3].

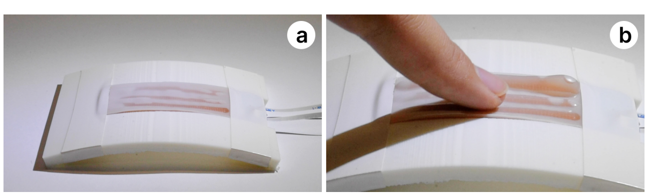

Figure 5: A shape-changing display on a curved surface showing wave-like visual and tactile animations.

Soft robotic fiber. We designed a soft robotic fiber by arranging four shape-changing units in sequence, each containing a reservoir that expands horizontally on both sides. Figure 6a-c shows the process in which the liquid in one shape-changing unit flows from one side to the other driven by the EOP, causing the unit to bend in one direction independently. By reversing the voltage inside this unit, the unit can bend in opposite direction. By controlling the independent bending behavior of each shape-changing unit along the fiber, the fiber can perform continuous shape-changing behavior across the entire length. Figure 6d-g shows four different shapes that the single fiber can switch between. This design demonstrates the potential of using FlexEOP to build multi-degree-of-freedom self-contained hydraulic soft robots.

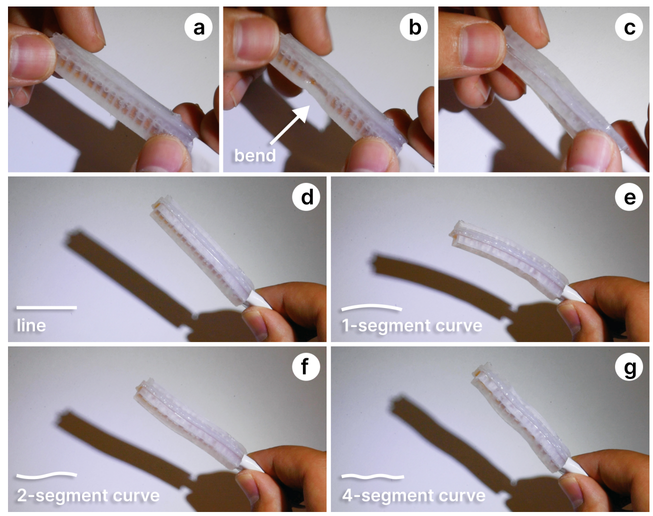

Figure 6: A soft robotic fiber composed of four shape-changing units that can perform independent bi-directional bending behavior. (a-c)The bending behavior of one single shape-changing unit. (e-h)Four different shapes that the single fiber can switch between.

4 CONCLUSION AND FUTURE WORK

In this paper, we proposed FlexEOP, a method to create flexible electroosmotic pumps to facilitate shape-changing actuators with high flexibility and self-containment.

Future work are threefold. First, several crucial technical questions remain uninvestigated, such as, how bending the device affects the hydraulic pressure of the electroosmotic flows, and what is the maximum bending angle before the device breaks. Second, psychophysical evaluations could be conducted to explore the application of the actuators as haptic devices on different parts of the human body, in order to support future smart wearable design. Third, further exploration of structures and materials could expand the significance of these actuators in the engineering field, such as exploring structures to provide complex hydraulic actuator motions, or exploring fabrication methods to build fully stretchable actuators. We expect this work could inspire various fields, including haptic interface design, actuator design, and soft robotics design.

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