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Soft Electrohydraulic Actuators for Origami Inspired Shape-Changing Interfaces

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ABSTRACT

In this paper, we present electrohydraulic actuators for origami inspired shape-changing interfaces, which are capable of producing sharp hinge-like bends. These compliant actuators generate an immediate hydraulic force upon electrostatic activation without an external fluid supply source, are silent and fast in operation, and can be fabricated with commodity materials. We experimentally investigate the characteristics of these actuators and present application scenarios for actuating existing objects as well as origami folds. In addition, we present a software tool for the design and fabrication of shape-changing interfaces using these electrohydraulic actuators. We also discuss how this work opens avenues for other possible applications in Human Computer Interaction (HCI).

CCS CONCEPTS

• **Human-centered computing → User interface toolkits**; **Human computer interaction (HCI)**.

KEYWORDS

electrohydraulic actuators; shape-changing interfaces; origami; fabrication

ACM Reference Format:

Purnendu, Eric Acome, Christoph Keplinger, Mark D. Gross, Carson Bruns, and Daniel Leithinger. 2021. Soft Electrohydraulic Actuators for Origami Inspired Shape-Changing Interfaces. In *CHI Conference on Human Factors in Computing Systems Extended Abstracts (CHI '21 Extended Abstracts), May 8–13, 2021, Yokohama, Japan.* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3411763.3451590

1 INTRODUCTION

Shape-changing user interfaces have the potential to blur the distinction between the physical and digital worlds, and fundamentally transform how humans interact with computers [17]. These interfaces physically transform their shape to render digital information and provide dynamic affordances depending on the user and context [34, 40]. Traditionally, they have been prototyped using electromechanical actuators and rigid assemblies [8, 9, 14]. However, there has been a recent push to develop them out of soft materials driven by advances in soft-robotics and mechanisms inspired by natural organisms [33]. The current generation of soft shape-changing interfaces often relies on fluidic actuators [25, 31, 43] or electroactive polymers [11, 12]. Fluidic actuators are relatively easy to fabricate but are slow and bulky as they requires external pumps and valves. In contrast, electroactive polymers are fast and compact but are difficult to fabricate and not easily accessible to designers and novice users.

In this paper, we introduce electrohydraulic actuators for shape-changing interfaces that are easy to fabricate like the fluidic actuators but that also preserve the performance qualities of electroactive polymers. They operate by interplay of the electrostatic and hydraulic forces. They offer a soft, silent, fast, self-contained and low cost alternative to develop shape-changing user interfaces. Our electrohydraulic actuators are inspired by the electrical characteristics of hydraulically amplified self-healing electrostatic (HASEL) actuators, [2, 21] which work by electrically moving fluid inside flexible pouches and can be fabricated through inexpensive tools and commodity materials [26].

Although a DC electric voltage drives the activation of our electrohydraulic actuators, it is the working fluid that redistributes and causes the shape change. Leveraging this working mechanism, we developed bendable actuators, which are activated electrically and are capable of sharp hinge-like folds. Using these novel primitives, we show sample application prototypes for actuating existing objects and origami-inspired shape change. We also developed a software tool to aid the design, fabrication and visualization of shape change of these actuators. Finally, we discuss the future prospects of these actuators in terms of possibilities for new actuator geometries, self sensing, and programmable shape-changing interfaces.

2 RELATED WORK

Our work builds on previous developments in shape-changing interfaces, especially on fluid driven actuation methods and electroactive polymers as well as electrohydraulic actuators.

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CHI '21 Extended Abstracts, May 8–13, 2021, Yokohama, Japan
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ACM ISBN 978-1-4503-8095-9/21/05…$15.00
https://doi.org/10.1145/3411763.3451590

2.1 Fluid driven Shape-changing Interfaces

Fluid driven shape-changing interfaces rely on air (pneumatics) or liquids as a working fluid to drive the shape change. In this section, we discuss both these types, critically looking at the current field with respect to the speed of actuation, manufacturing ease, and portability.

Inspired by developments in soft robotics [16], pneumatic actuation is an emerging prototyping technique for soft shape-changing interfaces and has been used for a variety of applications and prototypes like volumetric display [18], inflatable Mouse [22], physical buttons [15], shape-change garment [32], haptic jackets [7], etc. It has been used to prototype shape-changing interfaces at various scales, both small [25] and large [36], primarily due to its ease of fabrication. These pneumatic shape-change primitives can be fabricated with a wide range of materials and techniques e.g. silicone rubber through a molding/casting technique [43] or thermoplastics through heat-sealing [29, 31].

Although the soft, lightweight, and easy manufacturing aspect of pneumatic actuators are encouraging, they invariably require an external fluid source for inflation and deflation. They must be tethered to rigid, noisy, and bulky pumps and valves through tubing, restricting their speed of transformation and portability. Alternatives such as a chemical reaction inside a heat-sealed pouch for pneumatic inflation have been explored [42], but rapid actuation through pneumatics is still not possible. Our electrohydraulic actuators maintain the benefits of pneumatics, and in addition offer a fast, silent, and integrated actuation method of prototyping shape-changing interfaces, free from external pumps and valves.

Closely related to shape-changing interfaces based on electrohydraulic actuators, a number of user interfaces utilize liquids inside deformable pouches to render haptic sensations or to change their shape. They often explore the unique properties of unconventional liquids such as magnetorheological (MR) fluid [19], liquid metals [24, 30], colored liquids [27] and liquid to gas phase change [28]. Furthermore, these interfaces rely on external actuation methods such as electromagnets [19], heat [28] or pumps, [30] which are again bulky and slow. In contrast, electrohydraulic actuators can be fabricated from commonly available materials and do not rely on external air pumps or electromagnets for actuation.

2.2 Electroactive Polymers for Shape-Changing Interfaces

Electroactive Polymers (EAPs), offer a fast and portable alternative to pneumatics given their electric method of actuation. EAPs are polymers that exhibit an immediate change in size or shape when stimulated by an electric field [5]. Similar to EAP, our electrohydraulic actuators are also based on electrostatic actuation, which makes them rapid and silent in actuation.

Dielectric Elastomer Actuators (DEA) are a type of EAP which have been explored for applications in the domain of haptics [45], handheld shape-changing devices [35], and responsive environments [12], but they are limited in availability due to their high cost of the material and manufacturing [11].

In contrast, the shape change in our electrohydraulic actuators is effected by the movement of a working fluid through a simple heat-sealed pouch, which simplifies strategies for fabrication. In addition, the material used to build the device structure of our actuators are readily available and inexpensive, which opens deployment avenues in practical shape-changing application scenarios.

2.3 Electrohydraulic Actuators

Electrohydraulic actuators exploit the advantages of conventional hydraulic systems as well as direct-drive electrical actuators [13]. Traditionally, such actuators have been constructed from rigid electromechanical components [10] but recently soft versions have also been introduced [2]. While soft electrohydraulic actuation has been investigated for its basic working principle [2, 41] and for robotic applications [21, 41], its application to human-machine interfaces has been limited to haptic devices [23, 38]. There is a need to bridge the gap between material science technology and user-centered design practices for such actuators just as previous work in HCI community has done for hygromorphic bacteria [6, 44], or triboelectric nanogenerators [3, 4, 20, 46]. We present the detailed design, construction, and operating principle of electrohydraulic actuators for shape-changing interfaces. We also present a simplified design and fabrication process pipeline which can allow designers to creatively explore them for building origami inspired shape-changing interfaces.

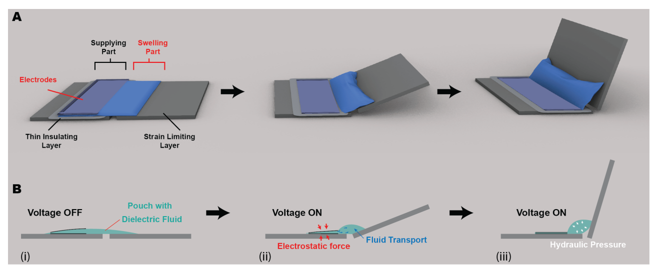

Figure 1: Actuation principle and design of electrohydraulic actuators that produce sharp bends. (A) Main components of the actuator with actuation states as the voltage is applied. (B) Principle of electrohydraulic actuation with electrode zipping as the voltage is applied.

3 SOFT ELECTROHYDRAULIC ACTUATORS FOR SHARP BENDS

The presented actuators for prototyping shape-changing interfaces utilizes a combination of electrostatic and hydraulic phenomena as well the composite material properties of the system (as depicted in Fig. 1) to produce sharp hinge-like bends. The actuators are activated by electrostatic forces, which displaces the working fluid to drive the shape change.

3.1 Actuator Construction

The actuator consists of four major parts as follows:

- **pouch** that is non-stretchable and compliant (Fig. 1B(i))
- flexible **electrodes** covering parts of the pouch (shown in purple in Fig. 1A)
- rigid **strain limiting layer** attached to one side of the pouch (shown in dark grey in Fig. 1A)

- **thin insulating layer** between the electrodes and the strain limiting layer (shown in light grey in Fig. 1A)

The pouch is filled with liquid dielectric (in this case silicone oil) and is divided into two parts: a supplying part (purple in Fig. 1A), and swelling part (blue in Fig. 1A). The supplying part is covered with opposing flexible electrodes on both sides.

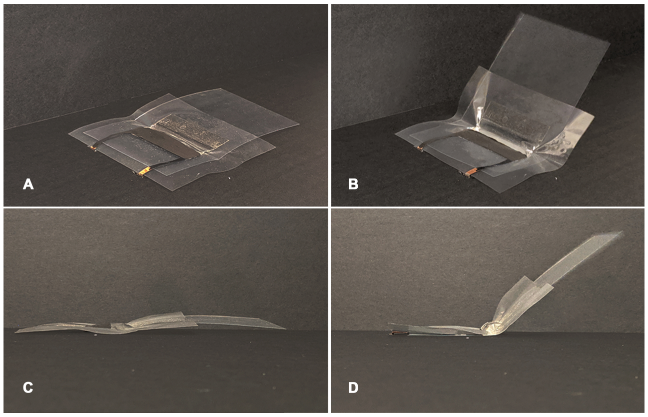

Figure 2: A simple origami fold actuation using electrohydraulic actuator; (A) Voltage OFF perspective view; (B) Voltage ON perspective view; (C) Voltage OFF side view; (D) Voltage ON side view.

3.2 Operation Principle

The operation principle is illustrated in Fig. 1 B. When the electrodes on the supplying part are activated by an external high-voltage input (8 kV in this case), opposite charges appear between them and the electrodes progressively pull each other (zipping motion) through an electrostatic force (Fig. 1 B (ii)). This pushes the dielectric fluid from the supplying part to the swelling part. This process continues with increasing applied voltage until equilibrium is reached between the electrostatic forces and restoring hydraulic pressure (see Fig. 1 B(iii)). The pressure increase in the swelling part causes it to inflate, and the cross-section of the pouch changes from a thin ellipse to a thick ellipse (see Fig. 1 B(iii)). This shape change combined with the rigidity of the strain-limiting layer results in angular deflection of the actuator (maximum angle generated at 8 kV is 80^o). The bending angle is also adjustable between 0^o-80^o proportional to the applied voltage. An image of the actuator with ON and OFF state is presented in Fig. 2. For the bending actuator the maximum weight lifted without reduction in bending angle was 13 grams (for a pouch with dimension 2cm x 4cm and liquid volume of 3ml) corresponding to a force of about 130 mN.

3.3 Materials

The construction of electrohydraulic actuators is highly dependent on the materials used for their components. The outer pouch that is non-stretchable and compliant is constructed out of heat sealable PET (polyethylene terephthalate; thickness, 22 μm) sheets. The dielectric fluid used in this work was silicone oil (Super Lube, 100 cSt). The flexible electrodes were painted using conductive carbon paint (Ted Pella, ELECTRODAG T-502, 30G). The strain limiting

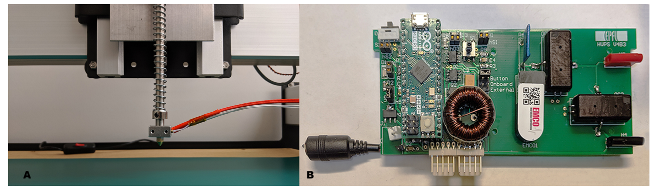

Figure 3: Electrohydraulic actuators are a hybrid of fluid-driven actuators and EAPs. They can be fabricated by (A) Custom Heat-Sealing Tool and (B) powered by a DC high voltage power supply

layer has two types: one constructed from transparency sheets (C-Line 60837) and the other using rigid acrylic blocks (thickness 6mm). The thin insulating layer between the electrodes and the strain limiting layer are constructed out of transparency sheets (C-Line 60837). The power consumption for these electrohydraulic actuators is low (< 1 Watts) despite the high voltage due to low current consumption (40μm).

An electrostatic control system (see Fig. 3B) drives the electrohydraulic actuators. This modular power supply unit was based on the open source power supply developed by PetaPicoVoltron [1] which has been utilized to drive DEAs for applications in soft robotic grippers and active substrates [37].

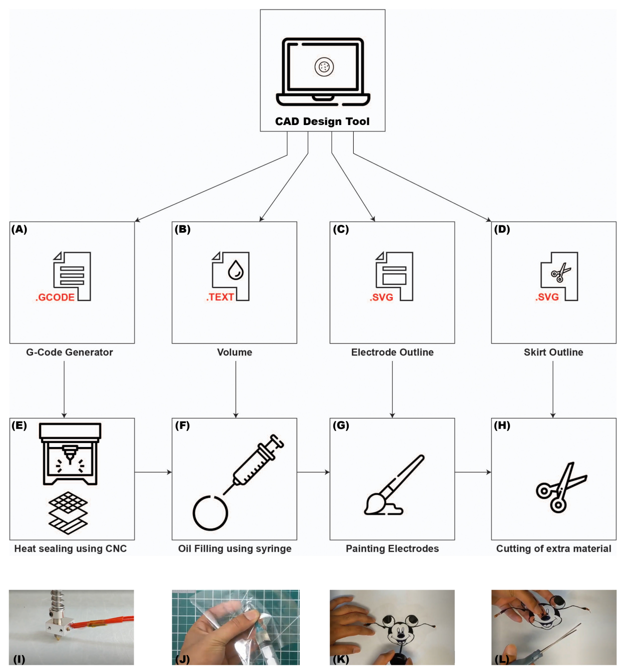

Figure 4: CAD Design Tool assisted fabrication pipeline for electrohydraulic actuators

To minimize the possibility of electrical damage, the thin insulating layer between the electrodes and the strain-limiting layer is very important, especially for HCI applications. Absence of such a layer affects the electrostatic activation of the actuator when attached to variable substrates, perhaps because the non-insulated electrodes come into direct contact of the substrate. We speculate that the unpredictable dielectric nature of the substrate interferes with the electrostatic activation of electrodes, which is countered with the help of the insulating layer.

4 DESIGN AND FABRICATION PROCESS

The electrohydraulic actuators are fabricated in four steps. First, the pouch is constructed by heat sealing two thin sheets of PET using a custom modified head of a 3-axis CNC (see Fig. 3(A) and Fig. 4(E, I)). A small input port is left in the heat sealed path for oil filling. Next, the dielectric liquid is injected manually using a syringe pump (see Fig. 4(F, J)) and the input port is heat sealed. Once the pouch is ready, electrodes are patterned manually using carbon paint (see Fig. 4(G, K)). Then, the extra material is trimmed, leaving a "skirt" (Fig. 4(H, L)). A skirt is needed to ensure that the electrodes don't arc through air at such high electric fields. An insulating layer is attached to the electrode base and then the desirable strain limiting layer is attached.

The accessibility and easy implementation of shape-changing interfaces enabled by our electrohydraulic actuators remains challenging as it involves great deal of experimentation with the amount of under-filled dielectric liquid and the electrode area.

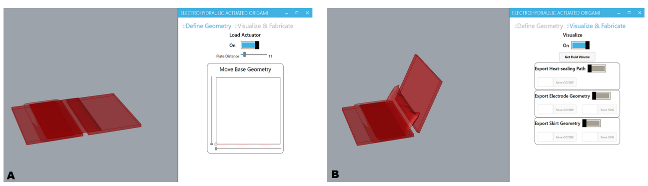

Figure 5: UI Design and Visualization window built in Rhinoceros 3D with Grasshopper environment. (A) The user can play with a pre-loaded geometry to optimize parameters. (B) They can also visualize the shape change and export fabrication files.

We developed a software tool to aid the design, shape visualization (not simulation) and fabrication of shape changing interfaces using the electrohydraulic actuators (selected screenshots shown in Fig. 5). The user can parameterize a pre-loaded actuator design according to use case and then visualize the shape change. The tool calculates the required volume of dielectric liquid to be filled in and also exports the fabrication files as g-code or SVG for heat sealing pouches, electrode fabrication, and skirt outline (see Fig. 4(A-D)).

5 APPLICATIONS

To explore the potential of shape-changing interfaces enabled by the electrohydraulic actuators, we present the following applications, along with the embedded actuator design and arrangements. Note that the figures do not show the power supply and batteries of the device prototypes.

Actuating Origami

Our electrohydraulic actuators have been designed to turn the creases of origami folds into active hinges. Some example prototypes based on this approach are shown in Fig. 6. A single sheet is folded into an origami crane, and the actuators are attached to the creases of the wings to move them. Likewise, a sheet folded into a box is augmented with actuators that open and close its lid. In both cases, the actuator transforms a static object into a kinetic sculpture. Numerous further origami designs exist that can be augmented through this technique in a calm, silent and unobtrusive matter. We envision applications for such kinetic origami in areas such as art, information physicalization, and tangible user interfaces.

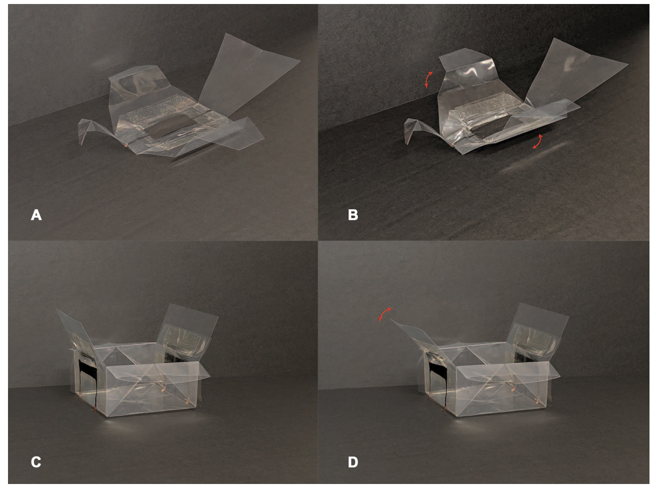

Figure 6: Using electrohydraulic actuators to actuate origami. (A) An origami crane with Voltage OFF, (B) with Voltage ON; (C) a box flap with Voltage OFF, (D) with Voltage ON.

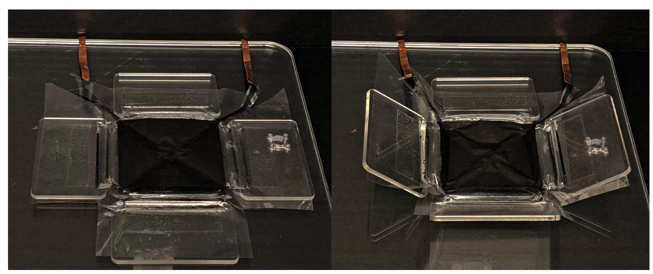

Figure 7: Example of shape-changing bowl

Shape-Changing Bowl

A group of electrohydraulic actuators can be arranged to form a shape-changing fruit bowl that transforms between a deep and shallow shape on demand (Fig. 7). The bowl is made of transparent acrylic panels that are connected to each other through electrohydraulic hinges. When small fruits are placed inside the bowl, the actuators lift the acrylic side panels to form a deeper bowl. When a large fruit is placed in the bowl, it transforms to a large, shallow shape by lowering the side panels.

6 DISCUSSION

The electrohydraulic actuators introduced in this work offer unique advantages in performance as well as ease-of-fabrication and offer great potential for the deployment of shape-changing interfaces in real-life scenarios. However, there is a need for thorough technical development as well as a user evaluation of the prototypes. As shape change for these actuators depends on fluid flow, there is also scope to develop other kinds of actuator geometries with novel functions. In this respect, it would empower designers to include a general simulation feature in the software tool to aid the discovery of new actuator form factors and applications. We also recognize the need for evaluating the software tool with end users.

Another limitation of the electrohydraulic actuators is the high activation voltage. Although even at voltages as high as 8 kV, the actuators are non-lethal, they can give painful shocks upon direct contact. This limitation can be solved by insulating the electrodes without compromising their compliance, a major direction for future work.

7 FUTURE WORK

Voltage of Actuation. Current actuation of these interfaces still occurs at high voltages (8 kV) which offers many challenges for day-to-day use, safety, and the cost of the control electronics. One way to achieve lower voltages would be to employ a different combination of dielectric polymer and dielectric liquid. Related work has demonstrated that sufficient insulation enables direct touch without risk of electric shock [39]. We plan to investigate how our electrohydraulic actuators behave with a similar soft insulating layer.

Extension of Shape-changing Behaviors. Other avenues for future work can be a broader and systematic exploration of shape-changing primitives of the electrohydraulic actuators. For example, the angular deflection must be characterized with respect to the load on the actuator (the mass it can lift). Verifying the complicated physics model of these actuators and simulating their behavior is an open problem and can greatly enrich the software tool. A software tool with well developed and evaluated user workflow can be a valuable resource for exploring more types of shape-changing behaviors.

Self Sensing: The inherent design of electrohydraulic actuator-enabled interfaces with capacitive electrodes and their model as variable capacitors offers possibilities for self sensing.

Programmable Shape-changing Interfaces. The current fabrication and insulation process allows the interfaces to morph between two shapes. It is still desired that the interface can have multiple shape-changing states that can be dynamically controlled in real-time. This might be achieved by introducing other active stimuli and it has the potential to become one of the major advantages of these actuators. The electro-hydraulic mode of activation opens up scope for multiple types of stimuli (different signals and voltages) to achieve active, fully programmable shape change.

8 CONCLUSION

We have presented electrohydraulic actuators to prototype shape-changing user interfaces. We demonstrate how these actuators can enable new application scenarios for origami inspired shape change and animating existing objects. We also proposed a software tool to aid the design, visualization, and fabrication of these shape-changing interfaces. This approach creates new opportunities to employ shape-changing interfaces by using responsive materials. We hope this work initiates novel conversations for building human computer interfaces.

ACKNOWLEDGMENTS

This work was supported by funding from the College of Engineering and Applied Science at the University of Colorado Boulder. We thank Nivedita Arora and Mirela Alistar for valuable suggestions in the draft and proof-reading, Ran Zhou for the help in preparing the video and Ryo Suzuki for early efforts in brainstorming.

REFERENCES

[1] [n.d.]. Project Peta-pico-Voltron. https://petapicovoltron.com/.
[2] E Acome, SK Mitchell, TG Morrissey, MB Emmett, C Benjamin, M King, M Radakovitz, and C Keplinger. 2018. Hydraulically amplified self-healing electrostatic actuators with muscle-like performance. *Science* 359, 6371 (2018), 61–65.
[3] Nivedita Arora, Thad Starner, and Gregory D Abowd. 2020. SATURN: An introduction to the Internet of Materials. *Commun. ACM* 63, 12 (2020), 92–99.
[4] Nivedita Arora, Steven L Zhang, Fereshteh Shahmiri, Diego Osorio, Yi-Cheng Wang, Mohit Gupta, Zhengjun Wang, Thad Starner, Zhong Lin Wang, and Gregory D Abowd. 2018. SATURN: A thin and flexible self-powered microphone leveraging triboelectric nanogenerator. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 2, 2 (2018), 1–28.
[5] Yoseph Bar-Cohen. 2002. Electroactive polymers: current capabilities and challenges. In *Smart Structures and Materials 2002: Electroactive Polymer Actuators and Devices (EAPAD)*, Vol. 4695. International Society for Optics and Photonics, 1–7.
[6] Xi Chen, Lakshminarayanan Mahadevan, Adam Driks, and Ozgur Sahin. 2014. Bacillus spores as building blocks for stimuli-responsive materials and nanogenerators. *Nature nanotechnology* 9, 2 (2014), 137–141.
[7] Alexandra Delazio, Ken Nakagaki, Roberta L Klatzky, Scott E Hudson, Jill Fain Lehman, and Alanson P Sample. 2018. Force jacket: Pneumatically-actuated jacket for embodied haptic experiences. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–12.
[8] Aluna Everitt, Faisal Taher, and Jason Alexander. 2016. ShapeCanvas: an exploration of shape-changing content generation by members of the public. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. 2778–2782.
[9] Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii. 2013. inFORM: dynamic physical affordances and constraints through shape and object actuation.. In *Uist*, Vol. 13. 2501988–2502032.
[10] Michel Franchet, Daniel Kettler, and Pascal Lejeune. 2004. Electrohydraulic actuator. US Patent 6,796,120.
[11] Karmen Franinović and Luke Franzke. 2019. Shape Changing Surfaces and Structures: Design Tools and Methods for Electroactive Polymers. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3290605.3300355
[12] Karmen Franinović, Luke Franzke, Florian Wille, and Andrés Villa Torres. 2019. Interacting with Electroactive Polymers in Responsive Environments. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Tempe, Arizona, USA) *(TEI '19)*. Association for Computing Machinery, New York, NY, USA, 505–512. https://doi.org/10.1145/3294109.3301268
[13] Saeid Habibi and Andrew Goldenberg. 1999. Design of a new high performance electrohydraulic actuator. In *1999 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (Cat. No. 99TH8399)*. IEEE, 227–232.
[14] John Hardy, Christian Weichel, Faisal Taher, John Vidler, and Jason Alexander. 2015. Shapeclip: towards rapid prototyping with shape-changing displays for designers. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. 19–28.
[15] Chris Harrison and Scott E. Hudson. 2009. Providing Dynamically Changeable Physical Buttons on a Visual Display. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Boston, MA, USA) *(CHI '09)*. Association for Computing Machinery, New York, NY, USA, 299–308. https://doi.org/10.1145/1518701.1518749
[16] Donal Padraic Holland, Colette Abah, Marielena Velasco-Enriquez, Maxwell Herman, Gareth J Bennett, Emir Augusto Vela, and Conor James Walsh. 2017. The soft robotics toolkit: Strategies for overcoming obstacles to the wide dissemination of soft-robotic hardware. *IEEE Robotics & Automation Magazine* 24, 1 (2017), 57–64.
[17] Hiroshi Ishii, Dávid Lakatos, Leonardo Bonanni, and Jean-Baptiste Labrune. 2012. Radical atoms: beyond tangible bits, toward transformable materials. *interactions* 19, 1 (2012), 38–51.

[18] Hiroo Iwata, Hiroaki Yano, and Naoto Ono. 2005. Volflex. In *ACM SIGGRAPH 2005 Emerging technologies*. 31–es.

[19] Yvonne Jansen, Thorsten Karrer, and Jan Borchers. 2010. MudPad: Tactile Feedback and Haptic Texture Overlay for Touch Surfaces. In *ACM International Conference on Interactive Tabletops and Surfaces* (Saarbrücken, Germany) *(ITS '10)*. Association for Computing Machinery, New York, NY, USA, 11–14. https://doi.org/10.1145/1936652.1936655

[20] Mustafa Emre Karagozler, Ivan Poupyrev, Gary K Fedder, and Yuri Suzuki. 2013. Paper generators: harvesting energy from touching, rubbing and sliding. In *Proceedings of the 26th annual ACM symposium on User interface software and technology*. 23–30.

[21] Nicholas Kellaris, Vidyacharan Gopaluni Venkata, Garrett M Smith, Shane K Mitchell, and Christoph Keplinger. 2018. Peano-HASEL actuators: Muscle-mimetic, electrohydraulic transducers that linearly contract on activation. *Science Robotics* 3, 14 (2018).

[22] Seoktae Kim, Hyunjung Kim, Boram Lee, Tek-Jin Nam, and Woohun Lee. 2008. Inflatable mouse: volume-adjustable mouse with air-pressure-sensitive input and haptic feedback. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 211–224.

[23] Edouard Leroy, Ronan Hinchet, and Herbert Shea. 2020. Multimode Hydraulically Amplified Electrostatic Actuators for Wearable Haptics. *Advanced Materials* 32, 36 (2020), 2002564.

[24] Qiuyu Lu, Chengpeng Mao, Liyuan Wang, and Haipeng Mi. 2016. LIME: LIquid MEtal Interfaces for Non-Rigid Interaction. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (Tokyo, Japan) *(UIST '16)*. Association for Computing Machinery, New York, NY, USA, 449–452. https://doi.org/10.1145/2984511.2984562

[25] Qiuyu Lu, Jifei Ou, João Wilbert, André Haben, Haipeng Mi, and Hiroshi Ishii. 2019. MilliMorph – Fluid-Driven Thin Film Shape-Change Materials for Interaction Design. In *Proceedings of UIST 2019* (New Orleans, LA, USA). Association for Computing Machinery, New York, NY, USA, 663–672.

[26] Shane K Mitchell, Xingrui Wang, Eric Acome, Trent Martin, Khoi Ly, Nicholas Kellaris, Vidyacharan Gopaluni Venkata, and Christoph Keplinger. 2019. An Easy-to-Implement Toolkit to Create Versatile and High-Performance HASEL Actuators for Untethered Soft Robots. *Advanced Science* 6, 14 (2019), 1900178.

[27] Hila Mor, Tianyu Yu, Ken Nakagaki, Benjamin Harvey Miller, Yichen Jia, and Hiroshi Ishii. 2020. Venous Materials: Towards Interactive Fluidic Mechanisms. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376129

[28] Koya Narumi, Hiroki Sato, Kenichi Nakahara, Young ah Seong, Kunihiko Morinaga, Yasuaki Kakehi, Ryuma Niiyama, and Yoshihiro Kawahara. 2020. Liquid Pouch Motors: Printable Planar Actuators Driven by Liquid-to-Gas Phase Change for Shape-Changing Interfaces. *IEEE Robotics and Automation Letters* 5, 3 (2020), 3915–3922.

[29] Ryuma Niiyama, Xu Sun, Lining Yao, Hiroshi Ishii, Daniela Rus, and Sangbae Kim. 2015. Sticky actuator: Free-form planar actuators for animated objects. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction*. 77–84.

[30] Ryuma Niiyama, Lining Yao, and Hiroshi Ishii. 2014. Weight and Volume Changing Device with Liquid Metal Transfer. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction* (Munich, Germany) *(TEI '14)*. Association for Computing Machinery, New York, NY, USA, 49–52. https://doi.org/10.1145/2540930.2540953

[31] Jifei Ou, Mélina Skouras, Nikolaos Vlavianos, Felix Heibeck, Chin-Yi Cheng, Jannik Peters, and Hiroshi Ishii. 2016. aeroMorph-heat-sealing inflatable shape-change materials for interaction design. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. 121–132.

[32] Laura Perovich, Philippa Mothersill, and Jennifer Broutin Farah. 2014. Awakened Apparel: Embedded Soft Actuators for Expressive Fashion and Functional Garments. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction* (Munich, Germany) *(TEI '14)*. Association for Computing Machinery, New York, NY, USA, 77–80. https://doi.org/10.1145/2540930.2540958

[33] Isabel P. S. Qamar, Rainer Groh, David Holman, and Anne Roudaut. 2018. HCI Meets Material Science: A Literature Review of Morphing Materials for the Design of Shape-Changing Interfaces. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–23. https://doi.org/10.1145/3173574.3173948

[34] Majken K. Rasmussen, Esben W. Pedersen, Marianne G. Petersen, and Kasper Hornbæk. 2012. Shape-Changing Interfaces: A Review of the Design Space and Open Research Questions. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Austin, Texas, USA) *(CHI '12)*. Association for Computing Machinery, New York, NY, USA, 735–744. https://doi.org/10.1145/2207676.2207781

[35] Anne Roudaut, Abhijit Karnik, Markus Löchtefeld, and Sriram Subramanian. 2013. Morphees: toward highs̈hape resolutionïn self-actuated flexible mobile devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 593–602.

[36] Harpreet Sareen, Udayan Umapathi, Patrick Shin, Yasuaki Kakehi, Jifei Ou, Hiroshi Ishii, and Pattie Maes. 2017. Printflatables: printing human-scale, functional and dynamic inflatable objects. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 3669–3680.

[37] Samuel Schlatter, Patrin Illenberger, and Samuel Rosset. 2018. Peta-pico-Voltron: An open-source high voltage power supply. *HardwareX* 4 (2018), e00039.

[38] Yitian Shao, Siyuan Ma, Sang Ho Yoon, Yon Visell, and James Holbery. 2020. Surfaceflow: Large area haptic display via compliant liquid dielectric actuators. In *2020 IEEE Haptics Symposium (HAPTICS)*. IEEE, 815–820.

[39] Y. Shao, S. Ma, S. H. Yoon, Y. Visell, and J. Holbery. 2020. SurfaceFlow: Large Area Haptic Display via Compliant Liquid Dielectric Actuators. In *2020 IEEE Haptics Symposium (HAPTICS)*. 815–820. https://doi.org/10.1109/HAPTICS45997.2020.ras.HAP20.23.0f334629

[40] Paul Strohmeier, Antonio Gomes, Giovanni Maria Troiano, Aske Mottelson, Timothy Merritt, and Jason Alexander. 2016. Sharing Perspectives on the Design of Shape-Changing Interfaces. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. 3492–3499.

[41] Majid Taghavi, Tim Helps, and Jonathan Rossiter. 2018. Electro-ribbon actuators and electro-origami robots. *Science Robotics* 3, 25 (2018).

[42] Penelope Webb, Valentina Sumini, Amos Golan, and Hiroshi Ishii. 2019. Auto-Inflatables: Chemical Inflation for Pop-Up Fabrication. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–6.

[43] Lining Yao, Ryuma Niiyama, Jifei Ou, Sean Follmer, Clark Della Silva, and Hiroshi Ishii. 2013. PneUI: Pneumatically Actuated Soft Composite Materials for Shape Changing Interfaces. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology* (St. Andrews, Scotland, United Kingdom) *(UIST '13)*. Association for Computing Machinery, New York, NY, USA, 13–22. https://doi.org/10.1145/2501988.2502037

[44] Lining Yao, Jifei Ou, Chin-Yi Cheng, Helene Steiner, Wen Wang, Guanyun Wang, and Hiroshi Ishii. 2015. BioLogic: natto cells as nanoactuators for shape changing interfaces. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. 1–10.

[45] Sang Ho Yoon, Siyuan Ma, Woo Suk Lee, Shantanu Thakurdesai, Di Sun, Flávio P. Ribeiro, and James D. Holbery. 2019. HapSense: A Soft Haptic I/O Device with Uninterrupted Dual Functionalities of Force Sensing and Vibrotactile Actuation. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 949–961. https://doi.org/10.1145/3332165.3347888

[46] Junwen Zhong, Qize Zhong, Fengru Fan, Yan Zhang, Sihong Wang, Bin Hu, Zhong Lin Wang, and Jun Zhou. 2013. Finger typing driven triboelectric nanogenerator and its use for instantaneously lighting up LEDs. *Nano Energy* 2, 4 (2013), 491–497.