Fluid Morphologies

Hydroactive Polymers for Responsive Architecture

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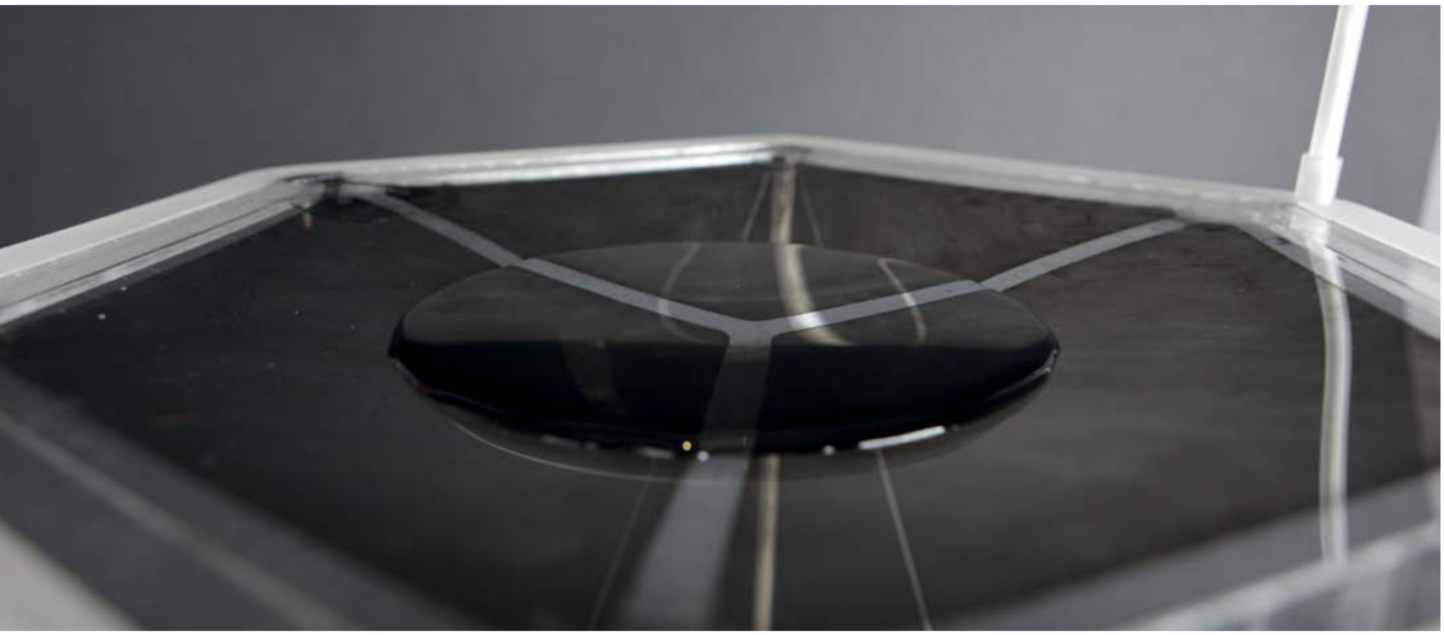

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1 Details of HAP device in the Fluid Morphologies installation.

ABSTRACT

This paper describes Hydroactive Polymers (HAPs), a novel way of combining shape-changing Electroactive Polymers (EAPs) and water for potential design and architectural explorations. We present a number of experiments together with the Fluid Morphologies installation, which demonstrated the materials through an interactive and sensory experience. We frame our research within the context of both material science and design/architecture projects that engage the unique material properties of EAPs. A detailed description of the design and fabrication process is given, followed by a discussion of material limitations and potential for improving robustness and production. We demonstrate fluid manipulation of light and shadow that would be impossible to achieve with traditional electromechanical actuators. Through the development of this new actuator, we have attempted to advance the accessibility of programmable materials for designers and architects to conduct hands-on experiments and prototypes. We thus conclude that the HAP modules hold a previously unexplored yet promising potential for a new kind of shape-changing, liquid-based architecture.

INTRODUCTION

One of the most exciting areas in design and architecture in recent years has come from practitioners engaging in new developments from material science (Rossi, Nagy, and Schlueter 2014; Decker 2015). In particular, a lot of attention has been given to shape-changing materials such as EAPs, which have been explored since the early 1990s in various material science labs (Biggs et al. 2013). It wasn't until the late 2000s that architects and designers began to work with them, typically to actuate structural elements. However, there is great potential for experimentation beyond simple kinetic activation, as we have demonstrated through our hands-on approach to EAP research.

We believe that this engagement of designers and architects with material science is best approached through an embodied, hands-on creative process, especially with regard to the unintuitive nature of elastomer deformations. We frame this paper and our research within the context of the Active Material approach, which explores the active properties of materials and sets out to uncover related aesthetic potentials (Franinović and Franzke 2015). The active materials we work with include those that can change their states and properties when exposed to certain stimuli such as humidity, light, or electricity. Hydroactive Polymers (HAPs), as described in this paper, work not only with the active properties of EAPs, but also with the active properties of water. Through the electrical actuation of HAPs, water oscillates and accentuates the movement of the module. In this interplay between electrical charges, the polymer response, and the dynamics of water, a complex material activity emerges and further involves people and the surrounding environment in interaction.

BACKGROUND

EAPs in Architecture/Design

EAPs have found their way into several architecture and design projects over the last several years. ShapeShift sought to imagine EAPs at an architectural scale through a speculative, adaptive facade prototype (Kretzer and Rossi 2012). The Homeostatic Facade System developed an adaptable solar shading system that took advantage of both the flexibility and reflectivity of an industrially produced EAP (Decker 2013). Reef implemented EAPs in a "living" ceiling (Mossé, Gauthier, and Guggi 2011). A Degree of Freedom integrated EAPs with rigid elements to create a dynamic structure (Rhoné and Genet 2014). Sound to Polymer proposed a dynamic wall surface which adapted in response to its acoustic environment (Joucka 2015). There has also been EAP Architecture research related to adaptive facades carried out through computer simulation and modeling (Krietemeyer and Dyson 2011; Stouffs 2013).

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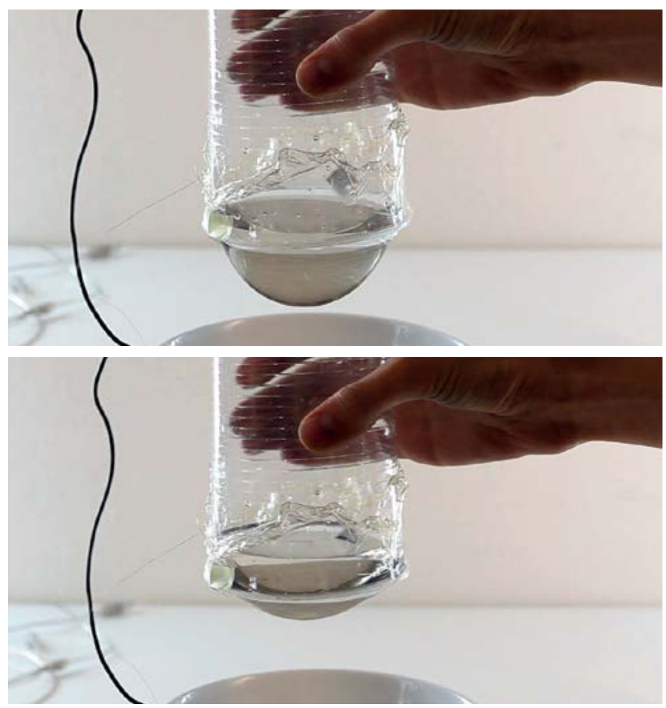

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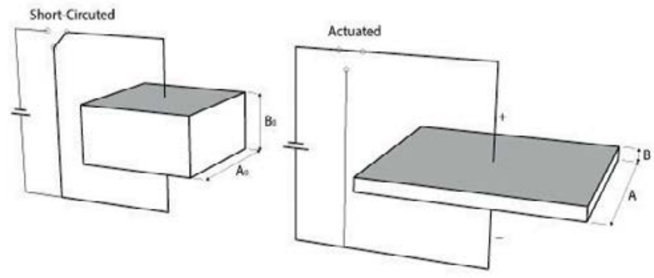
2 Details of installation construction showing the LED light source.

3 Video stills from the first experiment using water as an EAP electrode. See note 3.



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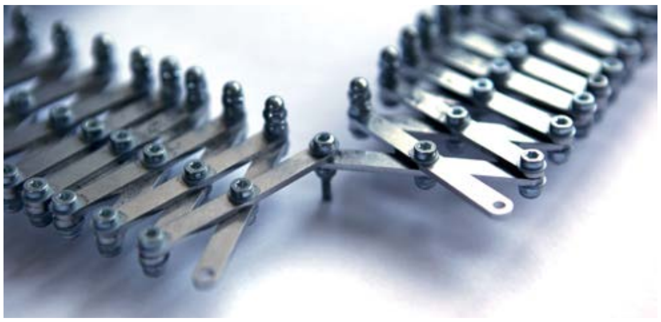

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So far, there have been few design-oriented projects that explore the optical properties of EAPs. Most notably, Kaleidoscope demonstrated variable color control through the contraction and expansion of tinted areas on the EAP membrane (Luna 2014). Similar effects have also been demonstrated in science literature, with EAPs used to emulate color-changing chromatophore cells in octopuses (Fishman, Rossiter, and Homer 2015).

EAP Functionality

The type of EAP technology used in this project is commonly referred to as a Dielectric Elastomer (Bar-Cohen, Sherrit, and Lih 2001). This type of EAP consists of two electrodes separated by an elastic dielectric material (Pelrine, Kornbluh, and Kofod 2000). When there is an electrical potential between the two electrodes, an electrostatic force compresses the elastomer, forcing it to expand laterally (Figure 4). When the two electrodes are short circuited, the elastomer returns to its original state.

EAPs provide a number of novel actuation possibilities that are difficult or impossible to achieve with traditional mechanical actuators. One of the most interesting aspects for designers is the organic movement that EAPs produce, an aesthetic counterpoint to the mechanical nature of traditional actuators.

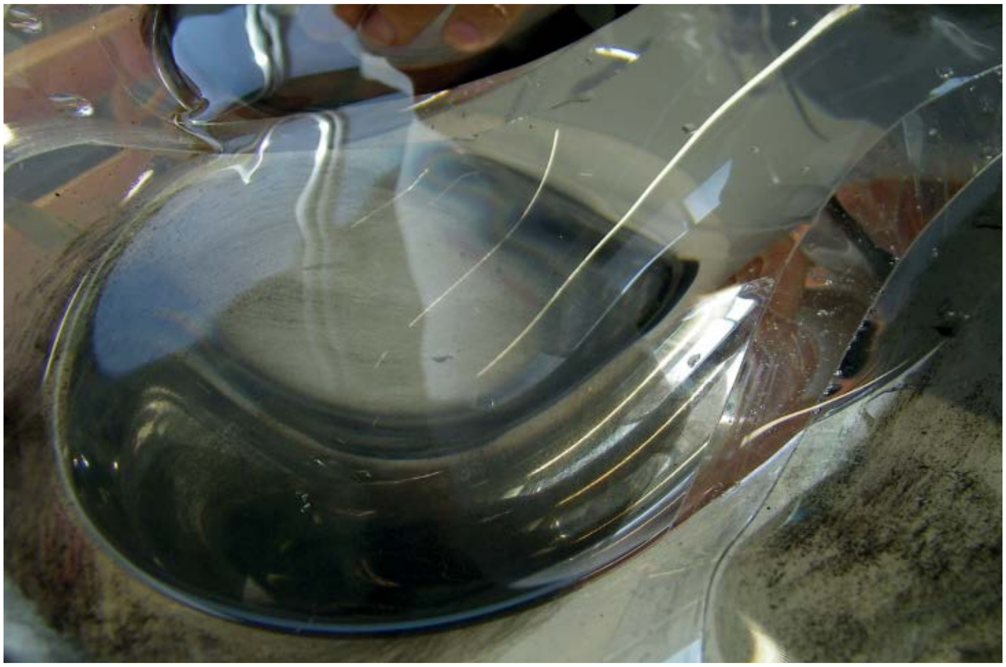
DIY EAP Fabrication Method

Our EAP fabrication method is based on techniques developed in the Laboratory for Mechanical Engineering Systems at the Swiss Federal Laboratories for Materials Science and Technology (EMPA). We learned the basics of this approach through hands-on instruction at the EMPA laboratories in Dübendorf. The process includes the use of a motorized biaxial stretching device capable of pre-tensioning thin membranes of VHB, a common double-sided adhesive tape produced by 3M (Lochmatter and Kovacs 2008).

Inspired by EMPA's approach, we built a manual biaxial stretching mechanism with opposing scissor-hinges (Figure 5). With this mechanism we were able to produce EAP actuators up to approximately 420 x 420mm from 1 mm 3M VHB Type 4910, although the same approach can work on a larger scale. After stretching to 250–350% of the original size, the elastomer was hand impregnated on both sides with Carbon Black (Ketchenblack EC300 from AkzoNobel), using a cellular foam applicator. We created detailed and repeatable patterns for electrically active areas with laser-cut stencils made from 3M backing foil. We demonstrated this technique in numerous workshops to enable other designers and artists to experiment and work with EAP actuators.[1] We developed a custom-built EAP driver for easy and programmable actuation of these DIY EAPs (Figure 6).

Liquids, Shape Control, and Tunable Lenses

Some examples of liquids combined with EAPs exist in material science literature, demonstrating applications for tunable lenses (Carpi et al. 2011; Maffli et al. 2015). Similar technology has also been used for tactile interfaces (Frediani et al. 2014; Carpi, Frediani, and Rossi 2010). However, these examples primarily function with enclosed volumes for tiny mechanisms, making them suitable for imaging applications and consumer electronics but



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4 The basic function of Dielectric Electroactive Polymers.

5 Details of Biaxial stretching mechanism.

6 Custom built EAP driver, developed by Florian Wille in 2011. The driver is Arduino based and relies on the EMCO GP50R to provide up to 5000V DC to eight programmable channels. Details of construction can be found at http://www.enactiveenvironments.com/enabling/eap-driver/.

7 View of an asymmetrical electrode experiment.

not for an architectural scale. The technique we developed shows that an open-construction water EAP, what we refer to as HAPs, can act as a large-scale programmable lens and shape-changing element. We also demonstrate that water can act not only as a compliant material, but also as an active part of HAP modules.

EXPERIMENTS WITH LIQUIDS

Our first experiments with liquids and EAPs began during the Contraction Expansion workshop run in collaboration with Liquid Things art research in Vienna, Austria (Franinović, Wille, and Korschner 2012). In preparation for the workshop, we experimented and prepared homemade electrorheological fluids (ERF) which harden when exposed to electricity. We used them in the workshop to connect two EAPs and to replace carbon black as an electrode. Both tests exhibited exciting possibilities for haptic sensations and interactions due to the hardening of the ERF.[2] During the workshop we decided to repeat these experiments with water due to the difficulty of preparing well functioning electrorheological fluids.

Vertical Movement

Water was tested as an electrode on a pre-stretched elastomer, with a carbon electrode on the underside. A wire was hung from above, contacting the water to provide electrical current. When activated, the EAP exhibited strong unidirectional deformation under the weight of the water (Figure 3).[3] In addition to impressive deformation under the weight of water, we discovered another benefit of using a dynamic electrode. When holes appeared in regions of the polymer, we moved the water away from that location and the undamaged part of a polymer would continue to activate. These early HAP experiments demonstrated the potential for exceptionally strong activation.

Lateral Movement and Interaction

In 2014, Karmen Franinović conducted a residency at the Liquid Things project where she further explored the phenomenon (Moñivas 2017). We experimented with two independent carbon black electrodes on the underside of the VHB with water as the electrode on the topside. When the electrodes were activated simultaneously, the movement of the water was vertical, similar to previous experiments. However, when they were activated independently, an oscillating movement of the water could be generated. The motion grew stronger as the pendulum effect gained momentum over the course of interaction. Changing the timing of the actuation modulated the rhythm of this movement. While pressing the buttons of the driver, we tended to begin synchronising our body movements with the movement of the water. Such interaction provided a sense of continuous physical engagement, despite a discrete button interface. Furthermore, curious visual effects were generated from the moving, irregularly-shaped water lenses (Figure 7).

Asymmetrical Electrodes

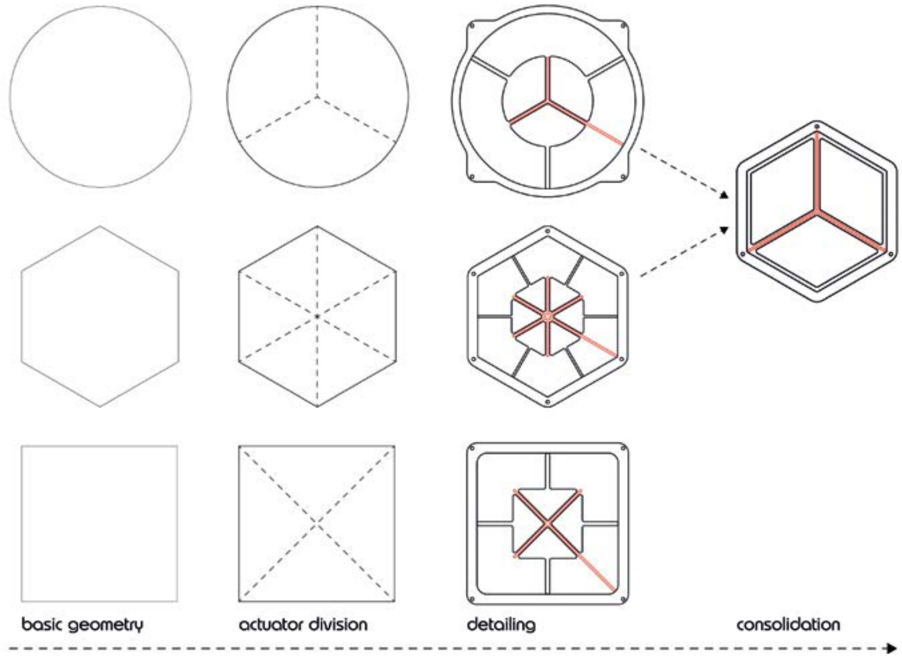
With the goal of finding the most dynamic movement possible, we tested asymmetrically shaped electrodes, which produced an irregular motion. In a further step, we combined several asymmetrical electrodes, resulting in a large deformation and dynamic

8 HAP geometry development. To reduce high stress regions the angles of the hexagon were filleted. Three actuation zones were chosen as the minimal number allowing a full range of motion.

9 From left: a) triangular tiling, b) rectangular tiling, c) hexagonal tiling, and d) rhombille tiling.

10 Detail of silicone touchpad interface.

11 Construction of silicone touchpad interface.



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movement of the water. The motion of the HAP varied based on the rhythm of the inputs provided by the user, the size and the shape of the electrodes, and the amount of water. Impressed by the range of motions and the engaging and complex interaction, we set out to develop a demonstration of these qualities.

Acqua Alta

The research developed over the course of the Liquid Things residency was directed towards an installation for the Venice Biennale of Architecture in 2014. The Acqua Alta project proposed an integration of dynamic HAP elements into a venetian beam ceiling. The shape-changing membranes were to perceptually destabilize the old wooden structure. They would move in relation to the real-time changes in water tides and the presence of visitors. The installation was intended to reflect the powers of water over the city of Venice and the human influences on the lagoon. Although the project was not constructed, the concept opened up new potential for ceilings, integrating dynamic elements and liquids into existing structures.

FLUID MORPHOLOGIES INSTALLATION

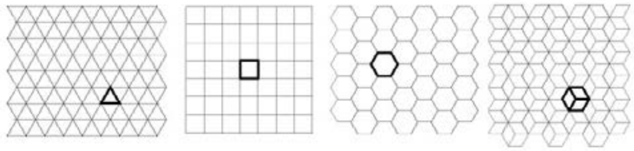
The Fluid Morphologies installation was developed for the Swiss Spirit exhibition at the Phillips Collection in Washington DC. The goal of our exhibit was to present the state of our research, but also to engage the visitors to interact with the material. Our installation combined EAP, water, and light into an interactive sculpture. The HAP module was divided into three separately actuatable zones on top of which water was suspended. An LED light source illuminated the water from above, creating shadow play below. A silicone-based touch interface mirrored the actuatable EAP zones and allowed visitors to control the movement of the EAP and water, and thereby distort the light.[4]

Movement and Interaction

We began by testing possibilities beyond the vertical up/down, and back and forth pendulum movement. We found that three electrodes enabled a circular motion of the HAPs, in addition to the up/down and pendulum motions. With careful activation of the three zones, it was possible to build up momentum for ever greater circular motion. The three active areas provided an optimal amount of shape control while still demanding focus and anticipation from the user to maintain control. Based on these experiments, we decided to develop a sculptural element with an interface that would allow the visitors to trigger and play with the various surface deformations.

Support Structure

We created a lightweight tensile structure to display the HAP modules, while allowing them to be easily replaced (Figures 1 and 2). The HAP modules connected to electrical contacts on the structure through self-weight in order to provide power for the three individual activation zones. The rigid elements were made from laser-cut, sandblasted plexiglas and the tensile elements from transparent nylon thread. Electrical wiring was discretely piped through channels and tubes. Additionally, the installation was designed to be disassembled and packed into a standard suitcase and reassembled on site.



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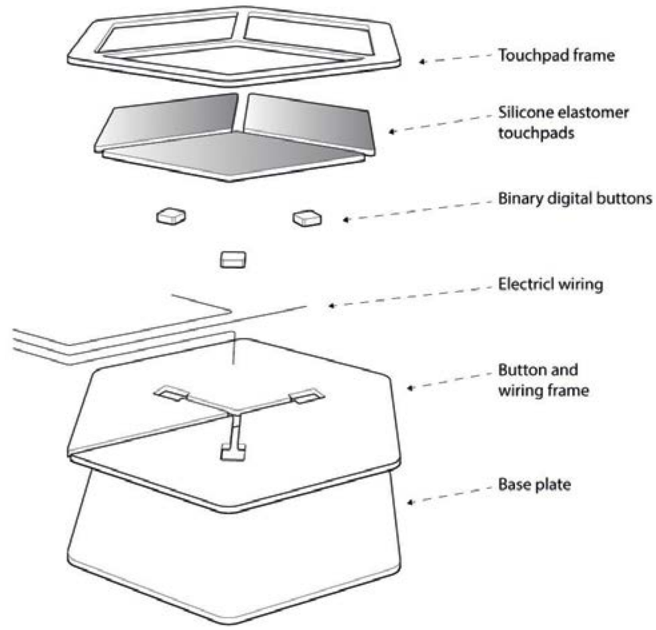

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Electrode Design

In our final design, the EAP electrode was composed of three individual activation zones within a hexagonal frame. This geometry was arrived at through a series of physical experiments that ranged in shape from triangles and squares to hexagons and circles. Our goal was to develop a module that could be easily combined into a larger surface and thus we explored tiling patterns. Triangles, squares, and hexagons were the three regular tiling (or monohedral) geometries we considered (Grünbaum and Shephard 1987) (Figure 9 a, b, c). The final geometry we chose can be tessellated through rhombille tiling (Figure 9d).

The hexagon geometry, due to its the wide angles, was closest to a circle. The latter, while not a regular tiling geometry, allowed for an even deformation of the thin EAP film element when actuated. Sharp corners cause regions of high stress in the thin film and can lead to material failure. The wide angles of the hexagon in combination with filleted corners helped us work around this issue while still enabling the regular tiling (Figure 8).

Interface

The installation was controlled through our EAP driver, together with a tactile interface designed to resemble the form and material qualities of the HAPs (Figure 10 and 11). A soft feel silicone controller was created, which allowed the user to activate specific areas of the EAP. Although the push-button interaction was discrete, the nature of the silicone touchpad lent itself to gradual application of pressure. In combination with the muscle-like movement of the HAP, this reinforced an illusion of continuous interaction.

New EAP Electrode Connection Method

One inherent challenge when working with EAPs is the interface between rigid and compliant elements. The VHB film is thinly stretched and at high risk of puncture when combined with rigid wires. Similar issues exist when working with other soft or unconventional electronic materials, such as e-textile (Perner-Wilson, Buechley, and Satomi 2010).

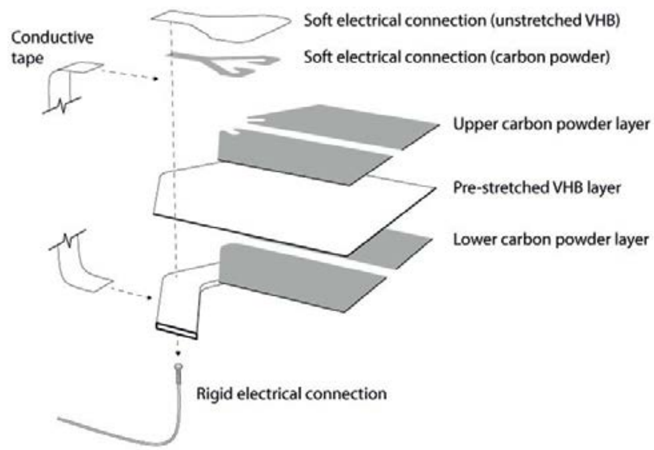
We overcame these issues by fabricating soft electrical connections to act as intermediaries between conventional wiring and the EAP (Figure 12 and 13). The connectors were assembled by stenciling traces of carbon black onto strips of unstretched VHB film. These strips then bridged between the wire terminals and the EAP membrane, so that the thinly stretched active areas would never be in direct contact with non-elastic electrical connections.

RESULTS

The results showed that different electrode constellations, combined with the water electrode, make the EAPs respond in a complex, fluid, and dynamic manner to gravity and user interaction.

Audience Response

The installation (Figure 14 and 15) was presented with two identical modules in order to allow several participants to control



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8 VHB based soft electrode connector.

9 Detail of VHB based soft electrode connector.

10 Visitors interacting with the two modules in the exhibition space.

the motion of the HAPs simultaneously. Due to the oversized nature of the touchpad, it was possible for a number of people to interact with the interface at once. During the event, we gauged visitors' impressions through direct observation of interaction and casual discussion.

It became obvious that the installation acted as an eye opener to the potential of such technology, not only in terms of architecture but also in robotics, design, and fashion. While visitors speculated at future applications of such technologies, they were most enthusiastic about aesthetic aspects of this dynamic material experience. These preliminary observations showed the importance of sensual interactions, as well as emotional and social aspects related to EAPs, which deserve to be examined in the future.

Material Response

One known limitation of do-it-yourself EAPs is the longevity of the extremely thin and delicate membranes. We had a certain degree of success in addressing this issue through our development of elastomer-based electrical connections, which reduced failure in this critical area. This new method greatly reduced issues related to puncturing of the VHB at electrical connections. This could also be suitable for applications beyond EAP, where soft electronic components must interface with rigid ones, as in e-textile fabrication.

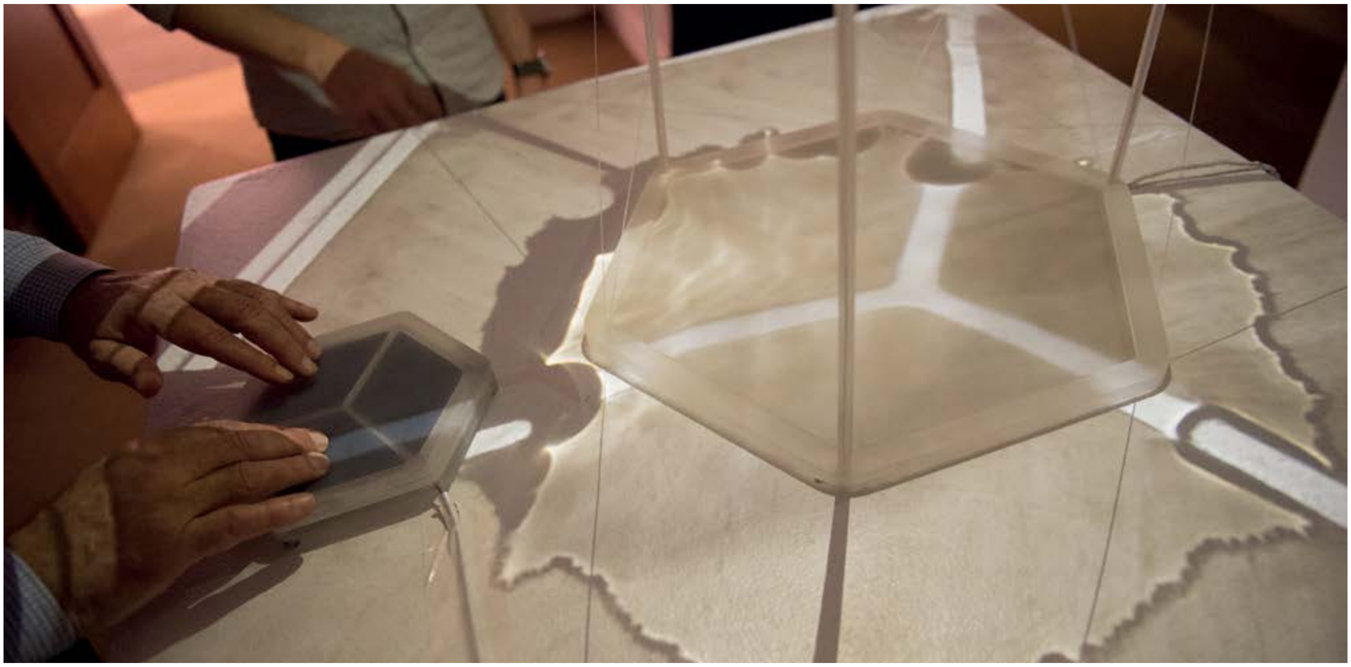
In our experiments, the VHB elastomer underwent rapid material fatigue. This appeared independent of the number of activations occurring, signaling that it is the weight of the water that strained the VHB elastomer and led to its deterioration. To overcome this constraint, we designed the structure for rapid exchange of EAP membranes via replaceable inserts. This was an intermediate solution, and other options for improving material fatigue remain to be explored. Silicone-based EAPs, for example, may offer greater robustness and potential new avenues for fabrication. Silicone-based fabrication methods demonstrated in material science have involved printing techniques and tools familiar to many designers (Rosset and Shea 2015), offering greater potential for knowledge transfer into design disciplines.

CONCLUSIONS AND FUTURE DIRECTIONS

In this paper, we described a novel HAP actuator that combines water and EAP to create a dynamic, shape-changing actuator. We explored the potential of these actuators through a number of experiments and demonstrated our outcomes with an interactive installation.

In order to improve the robustness of HAPs beyond our success with soft electrical connections, our future research will focus on experimenting with silicone elastomers to replace the more fragile VHB used in this project. Once these issues of longevity are addressed, we will be able to move our focus to a more architectural scale. Improvements to lifespan would open up possibilities for further design explorations of this programmable material. Future enquiries should also include a quantifiable analysis of the material performance, which was beyond the scope of this paper. Finally, the interaction with such a system on different scales must be explored in a structured way.

These improvements will enable us to develop a more robust dynamic and interactive ceiling system at an architectural scale (Figures 16 and 17). Such an installation would continue the line of research established by projects such as Stratus and Resonant Chamber, which explored the potential of responsive ceiling installations to deal with air quality and sound, respectively (Thün et al. 2012). Whether driven directly by people in the space, algorithmically, or by environmental parameters, an array of these dynamic lenses would create an immersive environment of rippling light.



15 Visitors interacting with the two modules in the exhibition space.

ACKNOWLEDGEMENTS

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NOTES

1. These results can also be reproduced by following our online video tutorials, at https://www.youtube.com/watch?v=uw8FLgiXsmk and https://www.youtube.com/watch?v=PgNKeqOCOKE
2. Video demonstration available at https://vimeo.com/53367582
3. Video demonstration can be seen at https://vimeo.com/161240281
4. Video at https://vimeo.com/163376887

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IMAGE CREDITS

Figure 6: Photo by Florian Wille.
Figure 15: Photo by Alexander Morozov, courtesy of the Phillips Collection.
All other figures by the authors.

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