Shape Changing Surfaces and Structures: Design Tools and Methods for Electroactive Polymers

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ABSTRACT

Electroactive polymers (EAP) are a promising technology for shape-changing interfaces, soft robotics and other novel design explorations. However, the uptake of EAP prototyping in design, art and architecture has been slow due to limited commercial availability, challenging high voltage electronics and lack of simple fabrication techniques. This paper introduces DIY tools for building and activating EAP prototypes, together with design methods for making novel shape-changing surfaces and structures outside of material science labs. We present iterations of our methods and tools, as well as use and evaluation in participatory workshops and public installations. We discuss unique aesthetic and interactive experiences enabled by the organic and subtle movement of semi-transparent EAP membranes. Finally, we summarise the potential of design tools and methods to facilitate increased exploration of interactive EAP prototypes and outline future steps.

KEYWORDS

Embodied Interaction; Programmable Materials; Electroactive Polymers; Active Materials; Smart Material Interfaces; Shape-Changing Interfaces

ACM Reference format:
Karmen Franinović & Luke Franzke. 2019. Shape Changing Surfaces and Structures: Design Tools and Methods for Electroactive Polymers. In *2019 CHI Conference on Human Factors in Computing Systems Proceedings (CHI 2019), May 4–9, 2019, Glasgow, Scotland, UK.* ACM, New York, NY, USA. 12 pages.
https://doi.org/10.1145/3290605.3300355

CHI 2019, May 4-9, 2019, Glasgow, Scotland, UK.

ACM ISBN 978-1-4503-5970-2/19/05...$15.00
DOI: https://doi.org/10.1145/3290605.3300355

1 BACKGROUND

1.1 Motivation

Electroactive polymers (EAP) offer exciting possibilities for a range of interests of the HCI community, from robotics [25], energy harvesting [14] and responsive facades [3] to accessible interfaces [29] and sensing technologies [4]. These and many more possibilities have been demonstrated through hundreds of publications dating from the early 90s, in fields ranging from material science, to chemistry, electrical and mechanical engineering. However, within design, prototypical applications of EAP are still rare.

In *Shapeshift* [15] architects and designers worked directly with material scientists in labs to produce an EAP facade prototype for the first time. This project stirred immense interest, but it was followed by only a few design projects. In *A Degree Of Freedom* [11], EAPs were used for a responsive kinetic structure and a novel fabrication process was developed using a robotic arm. In *Kaleidoscope*, a 3D printer was used to extrude transparent electrodes on a pre-stretched elastomer to create a transparent display with unique optical effect [45]. A number of other projects explore EAP for design applications with scenarios or simulations, but with no functional prototypes [6][16][35].

One reason for the lack of exploration of EAP by designers for novel applications is the limited availability of commercially produced actuators suitable for prototyping. Furthermore, those on the market are intended for niche industrial applications, with little scope for design experimentation. For most design projects, this means EAPs must be built from scratch. There has been some progress in rapid prototyping methods [26][34] and basic tutorials such as those made by the Soft Robotics Toolkit [46]. The issue of activating these DIY EAPs has received less exploration. To date, there has been no publication demonstrating DIY design tools with methods for both fabricating and activating EAPs. Furthermore, designers need tools both for fast prototyping, ideation and for creating compelling demonstrative prototypes with precision, detail, structural finesse and designerly qualities.

1.2 Tangible Interaction Frameworks

The ultimate goal of the research presented in this paper is to foster the design exploration of novel shape-changing interfaces. The ability to employ mechanisms of actuation broadens the possibility of tangible user interfaces (TUIs) to give additional layers of feedback and meaning [19]. The term *Actuated Interfaces* has been coined to describe such devices, where physical movement can be sensed by the user [27], similarly, *Shape-Changing Interfaces* aim to use this quality to enhance the user's experience [28]. *Smart Material Interfaces* has been coined to describe TUIs, where the properties of the smart materials blur boundaries between input, computation and output [37][22]. Most recently, the *Active Matter* approach described active materials as composites in which a non-active part changes its properties under the influence of an active part [36]. Our *Active Material* framework highlighted the need for an embodied understanding of the emerging material technologies, that can be difficult to grasp through purely analytical or conceptual tools [7]. This is especially the case in novel materials where the scientific literature is often streamlined towards achieving particular performance goals, rather than opening up material's potential through design exploration and prototyping.

EAPs present a feasible technology to realise interfaces across these frameworks while introducing unique possibilities for organic movements impossible with traditional mechanical actuators. EAPs are soft, malleable and stretchable, offering exciting design possibilities outside of traditional "hardware" interfaces. They can be employed as a stretch or pressure sensor, suitable for wearable applications [38] or as a self-sensing actuator [12]. EAPs have been demonstrated for refreshable braille displays [29] and for vibrotactile feedback [18]. In both cases, EAPs offer the possibility of fabricating highly dense arrays of actuators with a low profile and low power consumption, making them suitable for wearable or slim, sheet-like devices [1]. EAP has been demonstrated in functional shape-changing interfaces prototypes in *Morphees* [33]. Such shape-changing interfaces powered by EAP can offer new affordances by adjusting their physical form to suit the context and application. This range of potential for future devices highlights the need for new prototyping tools.

1.3 EAP basic principles

EAPs can be divided into Ionic Elastomers and the more common Dielectric Elastomers. For the purpose of this paper, we are referring to Dielectric Elastomer Actuators when we use the term EAP. Dielectric Elastomer are composed of a stretchable dielectric membrane, such as acrylic rubber or silicone, sandwiched between two compliant electrodes. When a high voltage DC potential is applied across the two electrodes, electrostatic attraction between the electrodes compresses the elastomer. This compression results in the elastomer being forced outward, creating a radial expansion (see Figure 1)[24]. When the electrical potential is removed, the elastomer returns to its original form. This simple planar expansion can be employed for a variety of movements, such as linear, rotary, oscillatory. Unlike mechanical actuators, EAPs are transparent, stretchable and exhibit organic, muscle-like movements.

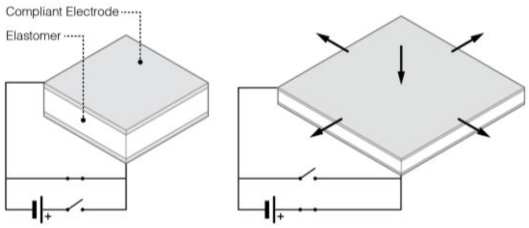

Figure 1: Planar expansion in EAPs with electrical activation

Multi-layered, stacked or rolled dielectric elastomers have been the subject of intense interest in material science research, due to greater power, scalability and redundancy. For these reasons, future commercial and industrial applications will likely use this construction. However, the advantages come with greater fabrication challenges. Furthermore, stacked or rolled actuators do not allow for the same range of forms factors and topologies. Single membrane EAPs offer unique aesthetic qualities due to their semi-transparency, lightness and organic movements.

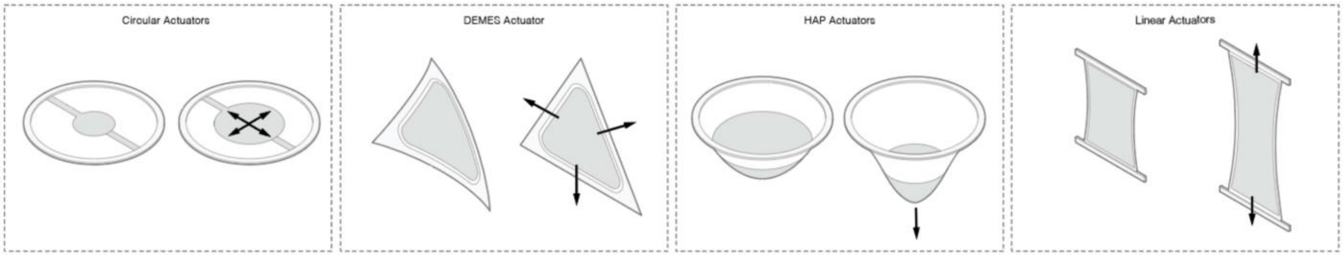

Figure 2. Four basic typologies for EAP actuators, arrows indicating direction of motion.

1.4 Design approach to material development

The EAP fabrication methods deployed in material science labs often make use of expensive lab equipment, or complex custom-built parts. In addition to this, many steps are made to guarantee conformity and reproducibility. This extends the production time and makes quick and exploratory prototyping difficult.

In the particular case of delicate EAP membranes, it is also beneficial to be able to quickly produce replacements (for example in an exhibiting or testing situation). Furthermore, our prototyping tools should be mobile and usable in a variety of contexts and be accessible for non-experts. In that sense, we follow a number of projects for DIY tools aimed at bringing new technological potential to designers and wider creative audiences [10] [20].

Our EAP tools and methods for prototyping outside of the material science lab have been developed iteratively and tested in participatory workshops and through our own design practice over several years. As a result, various iterations of these tools have already been deployed in completed projects under our guidance, such as in *Phototropia* [43]. These outcomes, together with projects described in this paper demonstrate that designers can fabricate EAPs with relatively simple means.

2 DESIGN TOOLS AND METHODS FOR EAP

The current version of our design tools and methods can be applied to four basic typologies of shell-like dielectric EAP actuators using both Silicone and Acrylic elastomers (see Figure 2). All of these actuators exert relatively weak forces, which limits individual actuators to moving lightweight structures and small loads. However, by combining multiple actuators, it is possible to increase the total force. These basic typologies can be used as building blocks for new forms of actuators. Figure shows how a Circular Actuator principle can be used to create linear motion. In *Fluid Morphologies* [9], multiple axes of movement were achieved with a single actuator with multiple electrodes (see Figure 4). Further examples of EAP actuators have been summarized by Anderson et al. [2].

Circular Actuators consist of the biaxially pre-stretched elastomer held in a rigid frame, with the inner region of the surface coated with a compliant electrode on both sides [40]. The tension in the elastomer allows for planar expansion of the electrode region when activated. Such actuator constructions have been demonstrated in tunable lenses [5] and artificial chromatophores [32]. The simple nature of this construction makes it ideal for quick demonstrations or material tests.

Dielectric Elastomer Minimum Energy Structures (DEMES) allow movement ranging from simple axial movement to complex, biaxial articulation. The nature of this movement is defined by the geometry of a compliant frame, together with tension provided by the pre-stretched elastomer to which the frame is attached. The tension in the elastomer pulls the frame inward, buckling it into a three-dimensional structure based on the frames thickness, profile and the level of tension. The membrane between the frame forms a hyperbolic, minimum surface. When activated, the tension is released from the structure, which will relax and flatten towards its original state.

Figure 3. A HAP actuator with additional movement axis, demonstrated in Fluid Morphologies [9]. Seen in motion in https://vimeo.com/163376887

Hydroactive Polymers (HAPs), follow a similar construction to Circular Actuators, but with water taking the place of one electrode. The HAP must be held in a horizontal position to contain the water. Such actuators are suitable for tunable lenses, deformable surfaces and for controlling light in architectural situations [9].

Linear Actuators can be constructed by tensioning the elastomer in a single axis. When the EAP is activated, the greatest surface expansion occurs in the direction of strain, allowing a linear motion to be achieved. These types of actuators are approximate to the range of motion of skeletal muscles [39].

2.1 Fabrication Tools

Our fabrication process deploys self-made tools for stretching dielectric elastomer and applying a carbon electrode. In addition, we use various cutting tools such as scissors, scalpel or laser cutter to produce DEMES actuators (PET or polycarbonate sheets) and rigid frame actuators (MDF, wood or plexiglass).

Our manual biaxial stretching mechanism (Figure 4) with scissor hinges is made of stainless steel in order to prevent the mechanism from bending. These steel parts are water jet cut and connected with 4mm screws. On the top side of the mechanism, rounded nuts are fixed onto the screws, to reduce tearing when in contact with the elastomer. The underside of the screws are used as anchors in holes positioned on the mdf guide, on which different stretch percentages are marked. The scissor stretch mechanism can also be produced from cheaper materials such as laser cut wood or even 3D printed plastic [23], but this does reduce the durability, maximum size and level of strain possible.

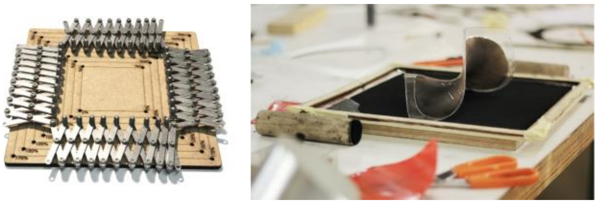

Figure 4. Stretch mechanism with scale guide, foam applicator with DEMES EAP

With this stretching mechanism, we were able to produce EAP actuators up to 420*420mm from 110*110mm 1mm acrylic elastomer, which is sold commercially as a double-sided adhesive tape (VHB 4910 from 3M). The scissor mechanism is a precise and convenient way to stretch the dielectric membrane, but it requires access to specialty tools for cutting steel sheets. We thus developed a simple radial stretch device for VHB using a shower hose and shared it through our tutorials (for example, youtu.be/uw8FLgiXsmk). However, this simpler DIY tool produces more VHB waste so we did not use it extensively ourselves.

For the creation of electrodes, we use a foam applicator to apply carbon black and a foam board to lay down the VHB foil during the impregnation. Both are made of plywood, with a layer of closed cell rubber (Maagtechnic PRENA CR/EPDM L7335) attached to the topside.

2.2 Acrylic Elastomer (VHB) Fabrication Methods

The basic fabrication approach involves pre-stretching 3M VHB 4910, which is commonly sold as a double-sided adhesive tape. At 250% to 350% stretch, carbon black (Ketjenblack EC 300 from AkzoNobel) is applied by hand to both sides of the elastomer. The resulting membrane can be incorporated into various configurations to achieve different types of actuation. Our DIY production methods draw from the approach developed at the Swiss Federal Laboratories for Materials Science and Technology (EMPA), where one of the first EAP design projects was prototyped [15].

The fabrication starts by cutting the VHB into squares and reinforcing their edges with narrow VHB strips. The VHB square is then fixed onto the scissor stretcher and stretched to the desired size. A rigid frame (for example, a wood or plexiglass frame) is stuck onto the VHB and its edges are reinforced with masking tape. The frame is cut out of the stretcher and the pre-stretched elastomer is ready for different types of EAP actuators. For flexible frame EAPs, we cut PET or Polycarbonate sheets by laser, scissors or scalpel. For rigid frames we cut wood, MDF or plexiglass by laser. As the VHB is self-adhesive, these frames can be easily attached with light pressure.

We hand impregnate the areas allocated for the electrodes with carbon black on both sides. This is a delicate operation, as carbon black must be gently rubbed into the membrane with a foam applicator. Non-uniform coating or folds in the VHB created by rubbing may result in a rupture due to electrical and mechanical forces. An optional stencil can be used for the electrode if greater precision is required. Areas that are not covered with carbon black can be puffed with glass powder. This reduces the adhesiveness of the VHB and the danger of the EAP sticking to undesired objects. Aluminium adhesive tape is applied in a suitable location on the frame to form contacts for both electrodes. Finally, excess elastomer is removed from the finished actuator with a scalpel.

2.3 Silicone Fabrication Methods

Fabrication with silicone allows familiar design processes such as mould making to explore unique forms for EAP and future design potentials. This method requires some additional steps compared to working with VHB, but it allows for greater control in the fabrication and for small productions a considerable cost reduction. Our initial experimentation with silicone, based on [30], has demonstrated a movement range similar to VHB actuators. The actuators we built appeared to have slightly less force (strain) and faster response times compared to VHB, which is in line with findings from material science researchers [17] [21] [41]. Silicone can be found in any design school workshop and is readily and cheaply available online.

The elastomer is prepared with two component silicone (ecoflex brand 00-30) which is mixed and degassed with a vacuum pump. The mixture is then poured onto a simple, 0.8mm deep mould which is levelled with a steel rod. After the mould has cured for 2-3 hours, or 1 hour in a 100°c oven, the cast is extracted from the mould. The cast is trimmed to a 100*100mm square and inspected for uniformity. The cast is then placed onto the scissor stretch mechanism and stretched 150% to 300%.

VHB can be easily impregnated with carbon black powder, as the particles stick to the adhesive surface. Silicone, however, repels most of the powder coating, so an adhesive electrode must be applied via a stamp or brush to silicone surface [30]. We were able to produce quick EAP prototypes using various cheap and readily available materials, such as conductive grease, electrode gel (such as those used for ECG) and even hair gel. While conductive grease offers the longest lifetime for the EAP, conductive gels are non-toxic and easy to apply. Further methods of creating compliant electrodes have been summarized by Rosset and Shea [31]. As silicone will not self-adhere to a frame, it must be either glued with a silicone adhesive or clamped in place. For HAP and Circular actuators, we prepared two sided plexiglass frames with magnets for clamping the elastomer in place.

Figure 5. Materials and tools for silicone EAP fabrication and a silicone HAP actuator with a supporting structure molded into the membrane.

2.4 The Open EAP Driver

The aforementioned tools and methods are relatively simple to reproduce, however, the high voltage involved (typically from 1000 to 5000 volts) is one of the largest barrier to the uptake of EAP in TUI's [33]. For this reason, we developed the Open EAP Driver, which is pocketable, programmable and can output up to 5000v while running of an internal battery. The device has push button activation and an onboard sequencer for cyclic testing and creative purposes. The high voltage output is provided with the compact EMCO A50 converter. The hardware is open source and the schematics and gerber files can be accessed from github for easy reproduction [47]. The interface has four main controls: power level, sequencer interval and duration and actuation. For interactive work or for working in combination with other devices such as Arduino, the driver can be activated by supplying a 5 volt signal to the control pins on the rear side of the interface.

Figure 6. Open EAP Driver

To simplify the construction and reduce material costs, the PCB (printed circuit board) acts as both the substrate for the electronics, a structural element in the electronic enclosure and as the user interface itself. We refer to this production approach as PCB-only, which has been popularized with a number of commercial products (e.g.[48]), but until now has not been described in the context of design research. This approach, while having a design appeal in its reductionism, also offers excellent manufacturing scalability, reduced material waste and simplified recycling.

The high voltages involved with EAP pose a risk of electric shock if used incorrectly. However, the EMCO A50 high voltage converter used here has a maximum output current limit of 0.20 mA according to the manufacturer. A number of sources place this at a safe level [44][42], should accidental shock occur. The inbuilt resistors in parallel to the load in our device also reduces the risk of an EAP holding a charge that could result in accidental shock. Needless to say, care must be taken when handling EAPs and the driver.

2.5 Explorative Fabrication Methods

Explorative fabrication methods have been a focus of our research for three reasons. First, the novelty of EAPs in design creates the need for exploration of its aesthetic and movement potential. Secondly, our approach is grounded on the premise that ideas should not be imposed onto materials, but emerge in a collaboration with materials, thus not forcing performance qualities. Last but not least, it can be frustrating to have repeatedly non-functioning EAPs after hours invested in their production. We thus created methods that enable faster material explorations by reducing prototyping time and complexity.

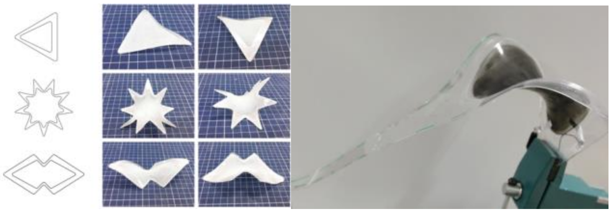

Figure 7. Explorative fabrication: Lycra mockups using and testing of an EAP frame cut by hand (vimeo.com/291931951).

When working with DEMES, one of the biggest challenges is finding a 2D frame design that will result in a desirable 3D geometry. A *lycra mock-up* method allows different shape deformations to be quickly tested. The mockups are made by pre-stretching lycra on the scissor stretch mechanism. The flexible frame is glued onto the pre-stretched fabric and cut out of the stretcher with a scalpel. Although this is not a precise simulation of the VHB, it is a quick way to test the frame deformation. This method also prevents wastage of the rather expensive VHB foil.

A second way to quickly prototype and test DEMES is by shaping them by hand using scissors or a scalpel, rather than laser cutting. This allows for very quick iterations: a wider frame than expected is cut and activated. If the 3D deformation is small, the frame is further cut. The designer also sees directly the impact of the frame geometry on the resulting deformation and movement. This method enables hands-on learning and is the most suitable for workshops and initial stages of prototyping.

3 WORKSHOPS AND INSTALLATIONS

The methods and tools presented in Section 2 are a result of an iterative process, in which they were refined over the course of seven years. The testing contexts include a number of workshops and installations. In this section, we present these events including their topics and goals, duration, locations, participants, workshop structure with tasks or installation goals, data collection, design outcomes and findings.

Overall, two types of data were collected during the workshops: the participant feedback and the design outcomes. The former was collected through personal interviews, group discussions and email questionnaires. Thus, the final data were texts on which we conducted content analysis. The goal was to identify information about how to improve our methods and tools, but also identify how the material potential is best explored. Participants were asked about the efficacy of tools and the hands-on process, the suitability of the workshop structure and facilities, their perception of the EAP and its potential for new ideas. The design outcomes were documented in photographs, videos and vector files. This data is presented here to show how our tools and methods affected the design exploration of EAPs.

3.1 *Actuated Matter*: First Fabrication Tools

In the *Actuated Matter* workshop [13], we used our VHB fabrication tools for the first time. The goal of the workshop was to explore how electrically activated materials could create responsive environment. The learning outcome for participants was intended to be an understanding of materials behavior through making. The creative goal was to connect EAP modules with other materials and explore their motion within a spatial structure. The workshop was developed with our colleagues from the Chair of CAAD in ETHZ and the Institute for Computer Music and Sound Technology, together with guests from Loop.ph laboratory, who had experience in DIY electroluminescent (EL) materials and lightweight spatial structures. The participants working with EAP used a product design workshop space. The workshop took place at the ZHdK over the course of five days in 2011.

In advance of the workshop, we prepared the first version of our fabrication tools that would enable us to create EAPs without the facilities of a material science lab. Also, we predefined the EAP morphology as a wooden Circular Actuator which could fit into a modular loop structure. The choice of using predefined EAP frame was based on our experience that developing new topologies is time intensive and potentially quite frustrating due to the large failure rate. Twenty participants included fourteen chosen from an online call for participation, two research partners, two guests organizers and two local organizers. They came from different fields including interaction design, architecture, sculpture, performance, film and sound art and various geographical areas including USA, Mexico, Australia, Austria, UK and Germany.

The first day started with lectures on different materials and responsive environments. These were followed by exercises aimed at identifying common values related to active materials. In the *Frankenstein Stories* exercise, participants were asked to describe a space made of active materials and related activities. Leaving only the last line visible, the paper was passed over to another participant who continued the story. The collectively written stories were then read by participants providing for shared imaginations and scenarios.

Figure 8. Placing acrylic frames and testing weight-based stretch.

The remainder of the workshop followed a hands-on approach, starting with the collaborative building of loop structures. The participants were showed how to bow fiberglass rods into rings and weave them into a spatial structure. Based on the lectures, exercises and material interests, the participants were asked to form groups: *EAP* group, *EL* group, *sound* group and the *Flow and Connect* group. The following three days of the workshop were dedicated to getting familiar with the material and developing modules to populate the spatial structure.

The *EAP* group was shown how to produce a predesigned module following the VHB method. A pre-lasered stencil was used for carbon black to create precise electrodes. The aluminium foil connectors were placed before fixing the circular wooden and acrylic frames on each side of VHB membrane. Glass powder was spread on the top of the polymer to reduce sticking (Figure 8). Participants were asked to repeat this process themselves in a learning by doing fashion. To reduce EAP failure, they were individually supported in critical steps of the process, such as rubbing in the carbon black homogeneously or attaching aluminium connectors.

On the last two days, the EAP, sonic and EL modules were integrated into the lightweight structure. Participants explored different ways of moving the light structural elements with Circular Actuators. For the activation of the EAPs, we used a driver provided by EMPA. The workshop ended by opening the exhibit to the public and documenting the results.

The design explorations were limited to the arrangement of the predefined Circular Actuator within the spatial structure and the resulting movements. Each module was attached to one loop in the structure. Their central plexiglass component was then connected to the structure with nylon cord, to other modules or to weights. The shape actuation resulted in a linear back and forth motion of the central piece. The EAPs subtly but noticeably moved the structure, especially where the structure was hanging open. At the locations with least degree of freedom, smaller loop areas were moved using two module couples (Figure 9). In addition, we connected two parallel loop surfaces with differently sized EAP modules. This resulted in a blob-like wall which expanded and contracted its different areas.

The organic motion of the whole structure was perceived by several participants as breathing. Two EAP module couples moving a part of the structure back and forth were described as the heart of the structure. The participants reported different reasons for this, including the timing of the activation, the look of the EAP membranes which exhibited wrinkle-like deformations and the location of the moving element within a protected structure resembling a lung.

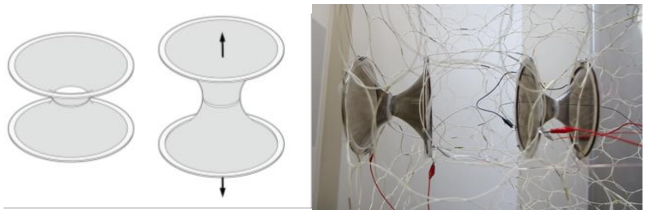

Figure 9. Two Circular Actuators connected by a plexiglass circle placed on the center of the VHB. Four actuators moving a small loop structure back and forth. Seen in motion at vimeo.com/310132880

All participants appreciated a hands-on approach and found tools to be easy to use. However, the EAP production was perceived as too meticulous and too slow. Participants appreciated that the basics geometry of the EAP was predefined. However, most of them wished they could have experimented with frame shapes, despite the greater challenges involved. Several participants wished to program the movement of multiple EAPs. We realized that the production process must be simplified and that learning how to produce a stable EAP material should not be done at the expense of design exploration. Our findings motivated us to research faster prototyping methods that could support exploratory experimentation.

3.2 *Alive Spaces*: Mockups and DIY Driver

Alive Spaces was an interdisciplinary workshop on shape-changing materials in which we tested a new DIY EAP driver and introduced the *lycra mock-up* method. The goal of the workshop was to develop novel DEMES frames and ways of connecting them that amplify their motion. Based on the results from the previous workshop, we decided to reduce the prototyping time: we did not to use glass powder, nor the stencils for carbon black. In order to enable quick exploration, we introduced lycra method described above. We developed the first iteration of a multichannel EAP driver programmable via an Arduino controller.

The workshop took place over three weeks in 2011 with eleven product and interaction design students at the ZHdK. The same location as in *Actuated Matter* was used, but this time the students had access to a laser cutter. A space was organized with working tables for each student and a testing desk with the EAP driver and a photo studio where the EAPs could be documented.

In the first week, we presented lectures and exercises investigating the relationship between aliveness and motion. In *Inspired Motion* exercise, students were asked to search for and video document movements that inspire them and classify them in a range of categories. The main challenge was to find movement that create associations such as “human”, “animal” or “mechanic”. This material was then used in *Design Moodboards* in which the students presented the aesthetic direction they chose to follow. On the third day, we asked students to develop mock-ups using the PET frame and lycra (Figure 7). In the second week, we introduced EAP tools and methods, and students begun to create working prototypes. In the third week, the task was to interconnect EAPs, choreograph and program their movement. Students worked individually and were mentored by two course leaders.

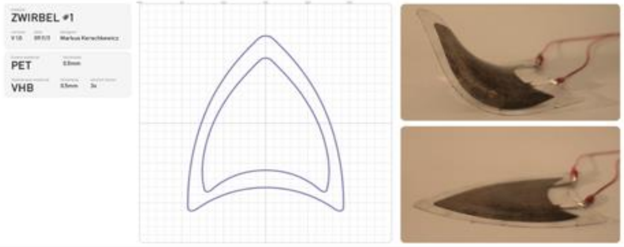

Figure 10. EAP template for Zwirbel module.

The feedback about tools and methods was collected individually through unstructured interviews. In order to collect the design outcomes, we prepared a template to record frame dimensions, two images showing the deformation and other information about the frame and the author (see Figure 10). The students were asked to show their modules to an outside audience and record their responses in a written form.

The final results were numerous shapes that ranged from organic forms such as butterfly wings to abstract but sensually moving modules. The motion of most modules was most often compared to animal or human movements such as birds flying or love making. The greatest challenge was connecting multiple EAPs without restricting the movement range. By varying the timing of the activation, some modules where mutually moving each other as if dancing (see Figure 11).

All participants appreciated the open exploration and the individual approach. They found this to be a motivating way to learn about a new material while following their own personal aesthetics. The use of tensioned lycra for prototyping the basics geometry was embraced, but half of the participants noted difficulty gluing lycra onto the PET frames. All of them appreciated the possibility to control multiple EAPs simultaneously via the new controller, although half of the students could not program it themselves. Most participants were frustrated in investing a long time developing the EAPs to then experience breakage on a first activation.

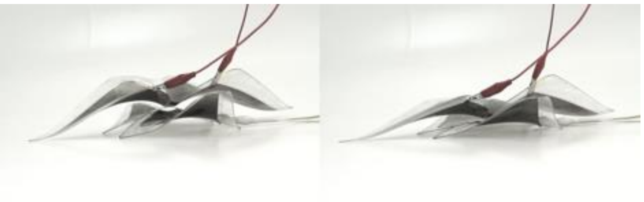

Figure 11. Two connected “dancing” EAPs. See motion at vimeo.com/106512539

3.3 *CoEx*: Quick Explorations

We therefore developed quick fabrication methods using scissors and a scalpel, which we tested in the three day *CoEx* workshop. The goal of the workshop was to apply the EAP in an artistic contexts and to contribute actively in the extension of the EAPs known possibilities. It was organized by invitation of the *Liquid Things* (LT) research group at University of the Applied Arts in Vienna. In advance of the workshop, together with the head of the LT, we explored the use of electrorheological fluids (ERF) and water with EAPs.

The participants were twelve master students from arts and science groups, one local organizer, two artists, one architect and two researchers from our group. They came from Austria, Greece, Iran, Serbia, Iceland and New Zealand and had a variety of skills from sound art to illustration. The workshop took place in the LTs spacious research lab in Vienna. The setup was the same as in the previous workshop, with a fabrication station and EAP activation/documentation station.

After quick introduction of the topic, tutorials and demonstrations of ERF/EAP, participants started individual explorations. The only task give to the participants was to explore new EAP forms. They were mentored individually by the three workshop organisers who tried to support different interests which ranged from animation to building architectural forms.

Feedback was collected in a group discussion and email questionnaires sent out two weeks after the end of the event in order to observe if the feedback changed overtime. We asked about the expectations from the workshop as well as about their own imagination and thinking processes during the workshop. Due to the short time, we did not use the template to document the work. Instead, EAP modules were video documented at their first activation (Figure 12).

This short event resulted in the largest variety of design outcomes that we managed to produce in a workshop context. The EAP types included animated images, robots, multi-electrode surfaces, HAPs, architectural models and others. The description of these and their perceived behavior is outside of the scope of this paper, but it is worth noting that the wide range of outcomes was enabled by substituting the laser cutting of the frames for the hand shaping by a scissor or a scalpel

Figure 12. Discussions at the activating/documenting station and EAP prototypes. See videos at: liquidthings.net/?page_id=1000

All participants were impressed by the potential of the material and satisfied with the working method. EAP failure was not perceived as frustrating for two reasons. First, because an immediate documentation of the EAP movement captured results before any failure. Second, if the EAP broke, its reproduction was quick due to a simplified production method. Overall, this was the most positive workshop feedback both in terms of process and design outcomes.

3.4 *SOLO:* First Public Installation

The goal of the *SOLO* project was to explore the possibility of empathising with an active material, but also to evaluate the possibility of using our tools and methods in a public context. This sound and light responsive space was created for the three-day Laokoon festival dealing with a topic of pain. We used a HAP with two hair gel electrodes on the bottom side which was enclosed and suspended above a moveable light source. Thus, only its shadow projection could be seen on a white surface on the ceiling and the walls. The light source was moved through a linear actuator and affected the focal length and thus the sharpness of the shadows. The movement of the HAP was triggered by algorithmically generated sounds and sounds made by visitors. The violent voltage peaks were damaging the material until it broke.

During the prototyping phase, we searched for a more transparent electrode material and discovered that a simple hair gel works. However, over the course of a day, it dried and hardened reducing movement and eventually resulting in a non-functioning electrode. Thus, a small EAP production facility had to be set up at the installation and new HAPs had to be made every day in advance of the event or when they broke. Our tools and methods made this an easy task.

Figure 13. SOLO (video at vimeo.com/219971330) and Electric Animals Plants

SOLO was the first time that we used the Open EAP driver. Two drivers were daisy-chained to control two EAP channels. They were operated via an Arduino connected to an electret microphone, programmed to trigger activation at certain peak volumes. This installation was a key testing ground for the flexibility of the Open EAP Driver, which proved to function reliably not only in a workshop setting but also for powering EAPs in an artistic installation.

Our second installation, *Electric Animals Plants [8]* used the same controller to run eight channels via WiFi connection. The setup of this installation was very quick, the EAPs were durable and the electronics functioned reliably over the course of four days. This project together with SOLO showed that our tools are at the stage in which they can be used for stable installations.

3.5 *Wunderkammer:* Silicone Fabrication

In the next the workshop, we used for the first time our EAP silicone fabrication method, and the Open EAP Driver. The workshop was a part of the three-day ZHdK event *Wunderkammer for Arising Matter,* which explored future directions in material design artistic research in 2016. Predefined rigid EAP frames were prepared for the workshop, together with all the tools and materials previously described for silicone EAP production. Participants comprised five researchers and PhD candidates in textile and architecture, familiar with various material practices, but with little or no experience of working with EAPs.

The spatial setup of the workshop was intended that the design outcomes from each day's work would accumulate in the space, developing into a wunderkammer that would inform developing discussion on creative practice. For the EAP component, participants were introduced to the silicone method for creating HAP actuators using water and hair-gel as electrodes. The participants could build the actuator within the predefined frame and were tasked with experimenting with different silicone densities in order to create a unique behaviour in the resulting actuator.

Figure 14. The testing setup for Silicone EAPs and example from the workshop

The design outcomes consist of video and images of the resulting EAP actuators and with various modifications by participants. Different variations of the parabolic form were achieved by modifying the distribution and density of the silicone (Figure 14).

Feedback was collected through group discussion and informal exchanges with participants. With the Open EAP driver, we observed that workshop participants could focus on playful experimentation and prototyping, without being hindered by the more technical aspects of the electronics. The sequencer also proved quite useful for simple tests and to build up more forceful oscillations in the HAP actuators using the bouncing motion of the water.

The silicone fabrication technique was perceived as complex and proved to require some practice and patience. This was a cause of some frustration as the actuator failed for one participant on the first attempt, perhaps due to uneven distribution of the silicone, or a foreign particle landing in the uncured silicone causing a weak spot. While these problems could be avoided, for shorter workshops it may be advisable to prepare silicone sheets in advance for participants.

4 FUTURE WORK

By continuing to simplify the silicone fabrication process, we intend to not only make EAP more accessible to designers, but also to open the possibility for radical new forms. The use of industrially produced silicone films, such as Elastosil from Wacker, could simplify the process and likely produce more reliable actuators but at the cost of reduced customizability. Currently, such films are cost prohibitive for many designers and we plan on providing further alternatives to creating and experimenting with them.

Our next steps include analysing our research related the aesthetics and perceived behaviour of EAPs. While this work was outside of the scope of this paper, we showed that design outcomes affected our development of tools and methods. Also, a number of qualities and criteria emerged in feedbacks from workshop participant and installation visitors, such as aliveness, decay, lightness, adaptation and responsiveness. We plan to publish and analyse this valuable information in a paper exploring EAP typologies, aesthetics and interaction.

5 CONCLUSION

In summary, we presented tools and methods that enable researchers and creative practitioners to explore and create with EAP technology. Both fabrication and activation of EAPs, together with the coding possibilities via a custom controller, were addressed. We showed how the final version of our tools and methods presented in Section 2 was iteratively developed through workshops and validated through public installations, as described in Section 3.

A number of findings emerged during our research that can be applied to research of any active material in design. Firstly, the value of handcrafting which emerged when developing EAP frames. We began our research by heavily relying on computational tools for design. However, we discovered that crafting by hand is highly beneficial for the exploration phase due to faster iteration possibilities. This supported our approach which allows the designer to gain an experiential and embodied understanding of materials qualities.

Secondly, the immediate documentation of the novel material behaviour proved to be of critical importance. This allows the recording of explorations and reflection on possible improvements and to inspire new ideas. In the case of fragile and unstable materials such as EAP, having a record of working experiments also increases the motivation for further exploration. This documentation approach also allowed us to capture moments in which we discovered new EAP behaviours for the first time, the contexts in which they were developed and the reactions of the team members involved. Such video material can provide valuable data for research on design laboratories and interaction design research processes.

The various contexts and audiences allowed us to reveal and find solutions for both technical and creative issues when prototyping with EAPs. This improved the accessibility and demonstrated that our tools and methods are at the stage where they can be used to create interactive EAP prototypes. Thus, the findings from this paper can be used not only by audiences addressed in our workshops, namely interaction designers and researchers in design, art and architecture but also by other interested HCI communities.

ACKNOWLEDGMENTS

We would like to thank Christa Jordi, Andres Villa Torres, Roman Kirschner, Manuel Kretzer, Mathias Gmachl, Rachel Wingfield, Daniel Bisig and all the workshop participants. Special thanks and acknowledgement go to Florian Wille and Dino Rossi for research contributions to this paper. Thanks for generous funding support to ZHdK, University of Applied Arts Vienna and Design Biennale Zurich.

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