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uniMorph - Fabricating Thin-Film Composites for Shape-Changing Interfaces

Felix Heibeck **Basheer Tome** **Clark Della Silva** **Hiroshi Ishii**
MIT Media Lab
Cambridge, MA, USA
{heibeck, basheer, clarkds, ishii}@media.mit.edu

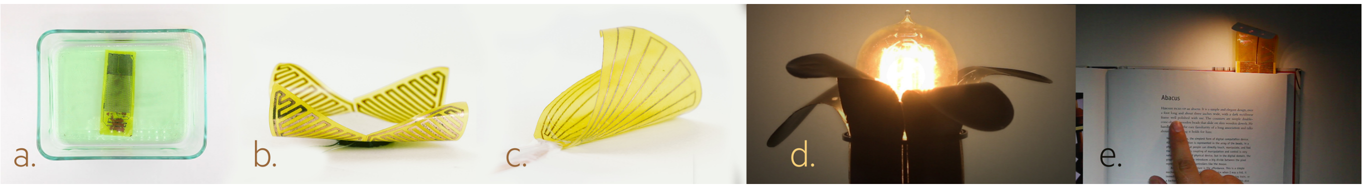

Figure 1. uniMorph contributes a rapid digital fabrication approach enabling designers to print custom shape-changing composites. With its multitude of capabilities for transformation and integration of electronics it facilitates a wide range of applications in shape-changing interfaces.

ABSTRACT

Researchers have been investigating shape-changing interfaces, however technologies for thin, reversible shape change remain complicated to fabricate. uniMorph is an enabling technology for rapid digital fabrication of customized thin-film shape-changing interfaces. By combining the thermoelectric characteristics of copper with the high thermal expansion rate of ultra-high molecular weight polyethylene, we are able to actuate the shape of flexible circuit composites directly. The shape-changing actuation is enabled by a temperature driven mechanism and reduces the complexity of fabrication for thin shape-changing interfaces. In this paper we describe how to design and fabricate thin uniMorph composites. We present composites that are actuated by either environmental temperature changes or active heating of embedded structures and provide a systematic overview of shape-changing primitives. Finally, we present different sensing techniques that leverage the existing copper structures or can be seamlessly embedded into the uniMorph composite. To demonstrate the wide applicability of uniMorph, we present several applications in ubiquitous and mobile computing.

Author Keywords

Shape-Changing Interfaces; Unimorph Actuation; Digital Fabrication; Rapid Prototyping; Human-Material Interaction; Organic User Interface; Radical Atoms

ACM Classification Keywords

H.5.2. User Interfaces: Miscellaneous

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INTRODUCTION

Recently emerged technologies such as OLEDs [6] or custom thin-film displays [28] release GUIs from their confined rigid form factor and offer to leverage the affordances we know from sheet-like materials like paper or other materials in our daily lives. The use of this new dimension for input possibilities has been explored in several papers [22, 31, 36, 38, 11], however there is considerably fewer work on active shape output for this medium [32, 9, 39]. One of the barriers to further research in this field is the complicated and expensive fabrication processes required to create shape-changing material mechanics. This paper addresses this barrier by proposing a thin composite layer actuator termed ”uniMorph” that is easy to prototype to enable more dynamic material interfaces.

Current shape-changing interfaces either rely on external rigid printed circuit boards (PCBs) or embedded flexible printed circuits (FPCs) designed for and fitted to the shape-changing medium. Thus far, design of these components has been separated from overall mechanism design. Shape-changing flexible circuits have been shown in robotic works [4, 27], however the presented composites are either non-reversible one-time actuation[4] or impossible to reproduce with common lab devices [27]. By combining the thermoelectric characteristics of copper with the high thermal expansion rate of ultra-high molecular weight polyethylene (UHMW PE), we are able to actuate flexible circuit composites directly. The shape-changing actuation is enabled by a temperature driven mechanism, similar to bi-metal strips [14] and dramatically reduces the complexity of fabrication. This enables more HCI researchers to design and fabricate thin-film shape-changing interfaces. The flexible circuit material of the uniMorph composite enables the embedding of sensors, additional actuators, or even micro-controllers - making it a true computational composite [37].

In this paper we present uniMorph, a thin-film composite for rapid fabricating of shape-changing interfaces. We explore its capabilities in the following categories:

- Design and fabrication of thin shape-changing composites with embedded sensing, control architecture and active shape output
- Primitives of uniMorph shape-changing which includes curvature change of surfaces; controlled hinging and assembly of 3D structures; programming of neutral state of the material.
- A survey of performance data for uniMorph composites
- Applications that demonstrate the benefits of this composite in HCI.

RELATED WORK

Digital Fabrication of flexible electronics

Recent interest in new form factors and shape changing interfaces has brought an advent of flexible printed circuits (FPCs). The low-cost and ease of fabrication with high precision make them an interesting medium for a wide range of projects from prototyping to complex DIY projects [35]. Research in inkjet printing with conductive inks [19] shows how flexible circuit fabrication can be moved from labs onto desktop printers. HCI projects like Gummi [33], Paperphone [22] and Snaplet [36] show how shape sensing can be integrated with flexible circuit sheets without sacrificing the flexibility of the material. The robotics field uses flexible circuits for resistive heating of pre-defined areas [4].

Flexible Sensing Technologies

A variety of sensing techniques on flexible surfaces have been explored in HCI. Bend sensor composites [22], optical sensors [5], and flexible capacitive sensing [11] are among common approaches to sensing human interaction and the material topology. Capacitive sensing techniques present a particularly interesting opportunity as they are able to detect human interaction and determine their own topology, while possibly also providing the architecture for electrical components.

Organic User Interfaces and Transitive Materials

The field of organic user interfaces (OUI) explores future scenarios as computationally controlled materials become commonplace [8]. The OUI movement is led by the idea that the physical shape of objects and displays will and should deviate from its current flat static form and become as malleable as the pixels on a screen [17]. This transformation is powered by transitive materials [8] that sense and conform to the users molding and actively drive its own shape-change [17]. While OUI research includes explorations into stiffness changing [29, 39] and stretchy mediums [21], we are most focused on sheet interactions in this context. Previous work on interaction with foldable [10] and flexible [22] sheet-devices are concerned with exploring them for malleable screens [28], more abstract forms [1], or materials including fabrics [7]. For thin sheet materials with active shape-change, techniques include soft user interfaces actuated by air pressure [39] as well as flexible mobile devices driven by nitinol [9, 32].

Shape Changing Sheet Technologies

The field of robotics is primarily concerned with the structural assembly of robots or sensors, as well as developing new techniques for creating stronger and faster shape-changing materials. In this paper, we are focused on making shape-changing techniques available to the HCI field. We leverage existing techniques like joule heating with copper, and combine it with cheap, accessible, and easy to fabricate materials to create a shape-changing composite and fabrication method that is reproducible for HCI researchers.

Self-folding robotics is a domain dedicated to developing autonomously self-assembling robots, often inspired by origami folding patterns [13, 26, 27]. In contrast with other electromechanical methods for self-assembly, self-folding robotics focuses on shape actuation material actuation mechanisms instead of motors or other external devices [13]. A large area of this research is dedicated to materials for self-assembly with non-reversible actuation. Shrinking sheet materials are used to assemble structural [4] and functional parts [34]. While some use external actuation energy like baking [26] or local light absorption [23], some researchers leverage the advantages of joule heating with thin copper traces for local heat actuation [4]. Previous work on reversible material shape actuation for sheets using nitinol [13] and electroactive polymers [27] is impossible to reproduce without expensive equipment. Piezoelectric actuators can be found in the same thin-sheet form factor [24], but have drawbacks that make them impractical for shape-changing interfaces. Primarily, a typical actuator only has a strain of 0.1%, requiring a 1m long actuator for 1mm of displacement. Piezoelectric materials are also extremely brittle and suffer from poor durability.

UNIMORPH ACTUATION

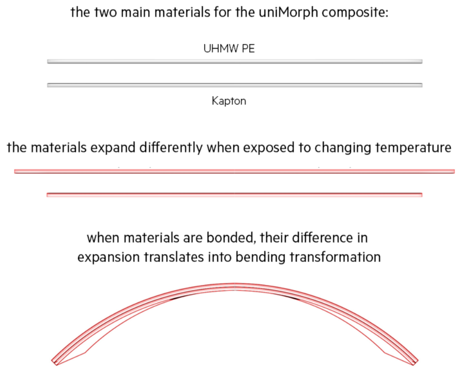


Figure 2. Different thermal expansion rates and resulting differential thermal strain lead to bending of the uniMorph composite

Two flexible materials with vastly different coefficients of thermal expansion composited together form a *unimorph actuator mechanism*. As the composite is heated, the material with the higher coefficient of thermal expansion exerts a shear stress on the adjacent material, causing the composite to bend perpendicular to the plane of the composite as seen in figure 2. Cooling the composite down bends the composite in the opposite direction. The actuation of unimorph actuators is fully reversible and well understood. Generally, the curvature can be described using classical laminate theory [12].

A variety of material combinations can be used to create this kind of unimorph actuator. For the composite presented in this paper (we call it ”uniMorph”), we use Ultra-High Molecular Weight Polyethylene (UHMW PE) and Pyralux® by DuPont® - a flexible copper clad with Kapton® as a carrier material. In addition to its availability and low price, we chose these materials for the high difference in thermal expansion and the possibility of easily embedding resistive heating by etching the Pyralux material.

Kapton and copper have similar linear thermal expansion coefficient of $\frac{20\times10^{-6}}{K}$ and $\frac{20\times10^{-6}}{K}$ while UHMW PE has a coefficient of $\approx \frac{200\times10^{-6}}{K}$ at 20°C. When heated up, the UHMW PE expands greatly compared to the Kapton, causing the composite to bend. When cooled, the UHMW PE shrinks faster, causing a bend in the opposite direction. The maximum composite temperature for reversible actuation is the working temperature of the UHMW PE (95°C). The speed at which the composite actuates is controlled by the temperature differential with respect to the environment. This allows for precisely controllable actuation with variable accelerations when heating the material. However, cooling speed is constant, leading to possibly asymmetric actuation times. Two approaches of addressing this behavior are presented in the upcoming section.

Passive Shape-Change

The easiest way of changing the temperature of a uniMorph composite is by modifying the temperature of its environment. Heat is a common waste-product of household and industry devices that is usually not utilized. Passively shape-changing composites offer interesting possibilities to use this excess energy for shape-actuation with functional and/or aesthetic purposes.

As seen in figure 2 one simply needs to create a two-layer composite of Kapton and UHMW PE (or other materials with a large difference in thermal expansion) to create a passive shape-changing composite. When the passive uniMorph composite is designed for light absorption, the composite should be darkened by either painting it or using black Kapton . Local light absorption as seen in Liu et al. [23] can be leveraged for actuating specific parts of the composite. Once composited, the sheet can be cut into arbitrary shapes by using digital fabrication tools like vinyl or laser cutters.

Active Shape-Change

For a uniMorph composite to actively change its own shape, it has to change its own temperature. As seen in Felton et al. [3], thin trace serpentine routing can be designed as resistive heating circuits to enable computational control of the composite's temperature (Figure 9). Custom design of resistive heating patterns allows for addressed heating of specific areas. These resistive heating structures can be easily integrated into a thin-film composite using a Pyralux, Kapton and copper laminate as shown in figure 3.

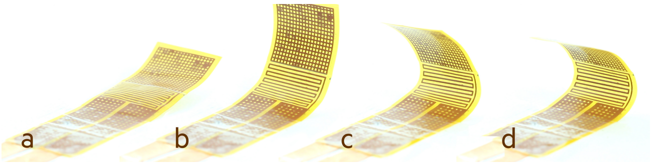


Figure 3. The uniMorph composite bending through resistive heating of copper traces.

The temperature of areas containing resistive heating patterns is controlled by the electrical power applied to them. Hence, the actuation extend and speed of the composite can be controlled through e.g. pulse-width modulation. This allows actuation speeds of under a second to infinitely slow for full actuation. Additionally, any position within the actuation range can be held by controlling the heat of the composite, ideally in a control loop as shown later.

While the increase in temperature can be computationally controlled with resistive heating, the cooling of a composite is normally solely dependent on its surrounding temperature and its thermal resistance and cannot be computationally controlled. We explored multiple ways of addressing this issue. Adhering a Peltier element onto the copper enables active cooling of the composite. Because of the high thermal conductivity of copper, the thermal energy is removed from the system efficiently. We found this method can increase the cooling speed up to 4x and additionally enables computational control of the cooling process. Another method is using pyrolytic graphite, a sheet material with even higher thermal conductivity than copper. By placing this material onto the copper layer of the uniMorph composite, the cooling speed can be increased about 2.2x without additional power usage. The two methods together add up to cooling speed, that is 5x faster than cooling with just environmental temperature change. Another advantage of using the copper layer for heating the composite is the ability to have multiple heating circuits that can be addressed independently. This enables multiple shape-changing behaviors with one composite as well as sequential actuation.

Neutral State Programming

Ultra high molecular weight polyethylene has a working temperature of 95°C. For reversible and repeatable actuation this temperature must not be exceeded. When its temperature exceeds this limit, the material undergoes a molecular reorganization, leading to a room temperature state of higher density that ultimately results in a pre-curled neutral state. Following actuation continues to work in a regular range. However, the resting position of the material is now bent and actuates to a straight sheet (Figure 11).

To achieve the pre-curled state, the composite can be either heated up in an oven or embedded heating structures can be used to pre-load the material. The latter method allows for a combination of flat and pre-curled neutral states in the same composite, since the heating elements are individually addressable. Alternatively, the materials can be composited at a temperature vastly different from normal room temperature, resulting in a partially actuated material in normal conditions.

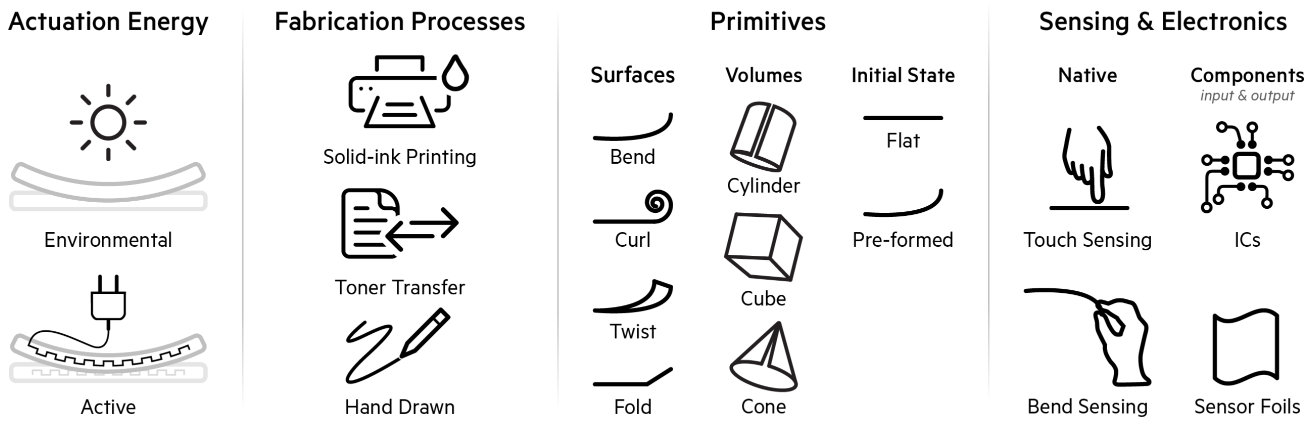


Figure 4. Four-dimensional design space for digital fabrication of custom uniMorph composites.

Active Composite Performance

When designing the uniMorph composite, several different factors affect the bending behavior of the composite. The most important factor is heater length, the length of the area covered by the resistive heating pattern. The longer the heater length, the bigger the maximum bending angle of the composite. When designing shape-changing composites with stiffeners (see section primitives), the most determining factor is is hinge length, which is defined as the length of the area in between two stiffeners. The larger the hinge-length, the larger the bending angle becomes. When using stiffeners the heater length has no noticeable effect on the bending angle as long as it covers the hinge length completely.

The actuation force (torque) of the composite is dependent on the thickness of the UHMW PE layer and the applied power. 12 mil thick UHMW PE film was used for the force tests. The sample was 1.5” wide with a 0.6” x 1.5” heating area and 1” x 1.5” area to lift. The tests were executed with an Instron force measuring system with constant power supply to the composite. While the torque is comparably small, it is still remarkable for the thickness of the composite.

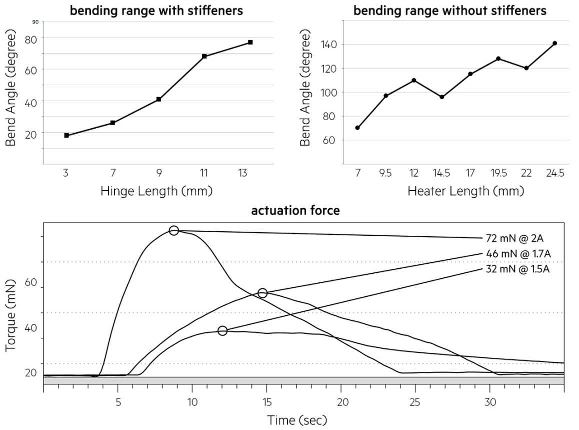


Figure 5. Hinge- and Heater-Length are the most dominant factors in determining the actuation range of the uniMorph composite. UHMW PE thickness and power control the actuation force.

DESIGN SPACE

Custom made uniMorph composites offer a variety of degrees of freedom for design. We found four dimensions for the digital fabrication of uniMorph composites that clarify the choices in design. This section provides an overview of these dimensions that will be described in more detail later. The design space is additionally illustrated in Figure 4.

Actuation Energy

The shape-change of uniMorph composites is powered by temperature change. Temperature change can be purely environmental or achieved by powering resistive heating elements in the composite. We define these modes of actuation as active and passive shape-change. Passive shape-change lacks computational control, but does not require any additional energy. Active shape-change on the other hand offers very precise and local actuation of the material while requiring energy. UniMorph composites can be designed for either passive or both passive and active shape-change.

Fabrication Process

We propose a digital fabrication approach for the production of customized uniMorph composites. For digital fabrication, the designer generates a digital pattern for the conductive layer as well as the overall shape of the composite using familiar tools like CadSoft’s Eagle or Adobe’s Illustrator. Ideally the pattern could be printed directly onto the Kapton using conductive ink and then automatically laminated. This would enable rapid prototyping with faster iterations. We show how to create uniMorph composites by printing patterns directly onto the Pyralux laminate using solid ink printing. The printed Pyralux is then etched in the same manner as in DIY PCBs. While solid ink printers are not widespread, this method comes closest to the instant process of automatic fabrication. Since solid-Ink printing is not available in most labs, we also present a toner transfer method that matches the quality of solid-Ink printing with slightly longer fabrication-times. Finally, we demonstrate a free hand prototyping method that does not involve digital fabrication but works by directly drawing onto the copper.

Shape-Changing Primitives

Customized uniMorph composites offer a variety of design options for shape-change as seen in Figure 8. The natural shape-change primitive is bending, which can be modified into curling and twisting. Materials that are stiffer than the film itself, which we call stiffeners, can be added to the composite to restrain and amplify the bending behavior. Using this technique, designers are able to create folds and three dimensional structures. While passive composite's shape-change is fully determined during its digital fabrication, active composite can change into multiple states since the actuation elements are individually addressable. Finally, the uniMorph composite's neutral state can be changed from flat to pre-curled by heating the composite higher than its working temperature.

Integrated Sensing & Electronic components

Sensing user input is crucial for using uniMorph in HCI applications. We present three ways of sensing user input on the uniMorph composite. One approach leverages copper structure as a sensor for both human input and its own topology. Alternatively, we show how the force resistive foil material Velostat® can be easily integrated into the uniMorph composite for force and bend sensing. Finally, the Pyralux laminate allows for easy integration of surface mount components - which significantly expands the sensing capabilities of the uniMorph composite.

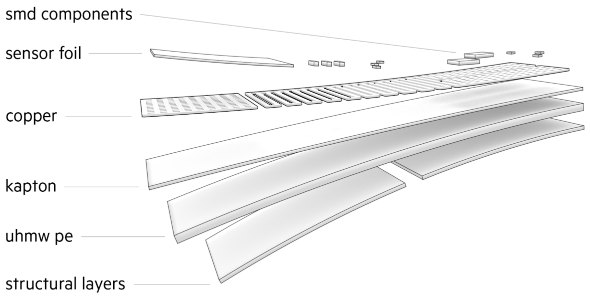


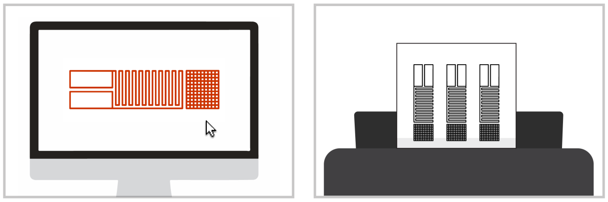
Figure 6. A diagram of all possible layers of the uniMorph composite. A passive composite would shape-change with just sheets of Kapton and uhmw pe. Copper adds active shape-actuation as well as the possibility of adding smd components and sensor foils. Structural layers restrain and define the composite's shape-changing behavior.

FABRICATION PROCESS

The fabrication of uniMorph composites can be divided into three steps. The designer creates a digital model of the composite structure (Figure 7.a), then fabricates this structure using print and etching methods (Figure 7.b-c), and finally composites the Pyralux laminate with the UHMW PE and other additional materials (Figure 7.d).

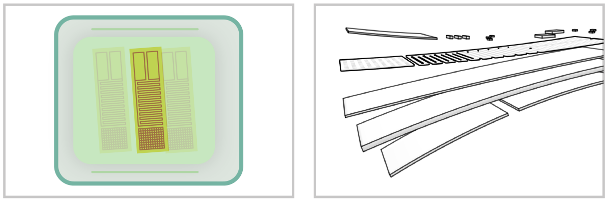
Digital Design

As with most active material composites, the range of possible shape-change is defined in the fabrication process [2]. The dominant factor for the behavior of uniMorph composites is the layout with its thin resistive copper heating traces.



1. Computational design

2. Printing onto copper



3. Etching / toner removal

4. Final compositing

Figure 7. The four step process for creating a uniMorph composite.

Designing heating elements of different shapes and distributions leads to new shape-changing behavior. The patterns can be designed with digital tools and then materialized through a bitmap print. This allows for the use of common applications such as Illustrator, Photoshop and Eagle for the digital design. Resistive heating elements are generated by creating thin copper traces that conduct high currents. We found the minimum width of traces that can be reliably fabricated to be 0.4mm (16mil) (see Figure 9). To heat up a designated area, a space-filling meandering pattern is used (as seen in Felton et al. [3]). Non-heating traces that carry load should be as wide as possible to ensure current supply to the heating areas without unwanted heat dissipation. Since the copper also makes up a large part of the material structure, the heating and transport patterns have to be designed in a way to support the material's deformation. Non-heating areas are filled with a hatched copper plane that combine high conductivity with the motion range of the flexible composite. For heating areas, the traces should go perpendicular to the bending direction to not interfere with the shape-change.

An alternative approach to digital design and print is using permanent markers to draw directly onto the copper-layer. While this method does not allow for the same accuracy as digital graphics and routing tools, it allows for faster and more expressive pieces. We also found this technique to be extremely useful to repair missing patches in the toner transfer method described later.

Fabrication

After designing the copper layer, the design is materialized through a bitmap print. The method available to most people is printing on glossy paper with a toner printer, followed by a heat transfer onto the copper layer of the Pyralux [16]. If available, a solid ink printer can be used to print directly onto the copper, eliminating the toner transfer [15]. We found that this method decreases fabrication errors and fabrication time while increasing the accuracy of the end product. Since solid

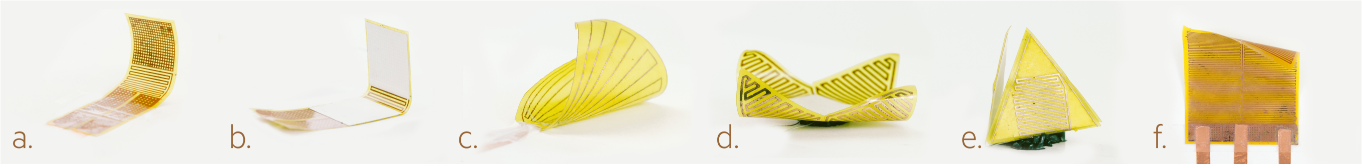


Figure 8. The uniMorph composite enables different shape-changing primitives derived from its bending mechanism.

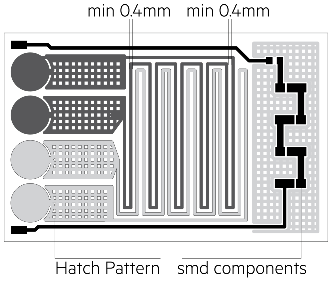


Figure 9. The copper-layer of the uniMorph composite enables resistive heat actuation. By creating two interweaving patterns (here seen in dark in light grey), the heating structure can also be used for bend-sensing through mutual capacitance. Furthermore, SMD components can be embedded.

ink printers are not commonly available, all design parameters and qualitative data presented in this paper are intended for or derived from the toner-transfer method.

After the print has been applied, the Pyralux is then placed in an agitated bath of 2 parts HCl, 1 part H_2O_2 until the bare copper is etched off. Once withdrawn from the bath and cleaned with water, the sheet is stripped off with acetone or other solvents. Finally a UHMW PE sheet is applied to the material. While we found the Kapton side of the composite to have better adhesive qualities, the sheet can also be adhered to the copper side for an inverted bending behavior. Pressure is applied to activate the adhesive, and then left to cure for at least 10 minutes. After curing, the laminate material can be cut to the correct dimensions either by using hand tools or a laser/vinyl cutter. Circuit components can be soldered using traditional solder methods. This should be done before adhering the UHMW PE sheet, as the high temperatures would affect the material. Finally, additional materials with stiffening, aesthetic, or other functionalities can be added to the composite. We successfully used the spray adhesive 3M Holdfast 77 to apply our desired modules, as it has good adhesion combined with high flexibility.

Stiffeners

Sheets of different materials can be applied to part of the uniMorph composite to stop it from bending in that applied area. In addition to its stabilizing and restricting properties, it also amplifies the bending effect in neighboring areas, as the thermal expansion of the material is redirected into these areas. To leverage this effect accordingly, the stiffened area and heating areas should be overlapping by at least 1 cm. We found sheets of paper between 100gsm and 130gsm to have the right balance of weight and stiffness.

SHAPE-CHANGING PRIMITIVES

The uniMorph composite's basic actuation mechanism is bending. The parameters for this behavior have been discussed in earlier sections. Depending on the area of the heating pattern and shape of the composite, the bending angle and curvatures vary. While short patterns will lead to small bending angles, long patterns will lead to very large bending angles. The composite can even curl up multiple times, if the composite has heating patterns all the way up to the edge. While bending and curling have already been used for a wide range of applications, more shape-changing primitives extend the applications for the uniMorph composite. In the following section we will show second order shape change primitives that are derived from the basic bending mechanism.

Addressability - One of the major advantages of the uniMorph composite is the ability to define heating areas for actuation. Regular bending perpendicular to the flat composite requires even heating of the composite in the bending area. When applying heat to only one side of the bending line, the heated side will actuate more and twist (Figure 8.f). This requires a relatively wide bending area to create a noticeable effect.

Folding - Some applications may require flat sheets that fold in defined areas (Figure 8.b). For example, parts of the composite might be populated with larger electrical components. By designing localized heating patterns, one can create bends with a relatively small bending radius. If more defined bending is needed, one can add sheet materials to the non-bending areas. As briefly explained before, this creates a folding effect with a higher bending angle while having the same length, since the thermal strain redistributes into the fold.

Volumes - While surfaces are already used for a wide variety of applications, the HCI field has an increasing interest in actuated three-dimensional structures [39] built with origami techniques. Using the folding mechanism, one can create simple origami structures that can self-fold and continue to move (Figure 8.e). Round volumes can be achieved by simple bending (Figure 8.c). These two actuation primitives can be combined to construct a multitude of dynamic three dimensional shapes out of the sheet composite.

Pre-Curling - The uniMorph composite can be set to a pre-curled state. As seen in the actuation section, the UHMW PE changes its density when heated higher than its working temperature. After being exposed to one heat cycle above its working temperature, the composite's neutral state is set in the opposite direction of its usual direction of actuation.

Figure 10. A lamp built from passive composites reveals light when blooming.

When fully heat-treated, the amplitude of this bend equals the inverse of the prior maximum actuation, while the new maximum actuation of a pre-curled composite is its neutral state. This makes it perfect for folded three-dimensional structures that open up when actuated.

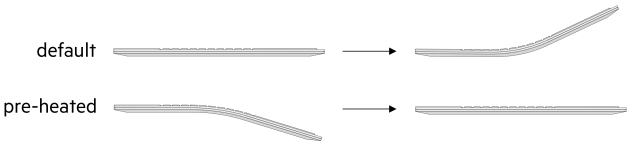


Figure 11. By heating the composite over its working temperature, a new neutral state can be set.

INTEGRATED SENSING & ADDITIONAL ELECTRONICS

Adding electronic components to shape-changing composites is crucial for building interactive prototypes. They complement the native sensing and actuation functionalities of the composite. Leveraging its copper layer, the uniMorph composite affords a multitude of extensions.

Capacitive Sensing for Touch and Topology

Because of its great conductance, copper can be used as a capacitive sensor element. This allows for not just the sensing of human touch or presence, but also the determination of material topology. When designed correctly, this meandering heating structure can double as a mutual capacitance angle-sensing mechanism. Instead of using a single trace for heating, two interweaving serpentine routes can be integrated as seen in Figure 9. This way, a mutual capacitance [39] can be measured between the alternating paths to infer the angle of the specific bending area. We found the accuracy of this sensing method to be about ±6 deg.

Capacitive sensing does not work during resistive heating phases, but a time-sharing implementation allows both functionalities using the same conductor without visible effects on the performance of the composite.

Velostat as force and bend sensor

A range of semiconducting materials can be embedded into the composite to provide additional sensing abilities. Velostat® is a pressure sensitive material that enables sensing the force of touch. When composited in-between the copper and UHMW PE layer, the differential strain between these layers compresses the Velostat. When positioned in the bending areas of the composite, the resistance of the Velostat can be used to infer the bend angle. We were able to achieve accuracy of up to ±7 deg. The resistance of Velostat also changes with heat, which has to be accounted for when writing sensing algorithms. The copper of the Pyralux can be used to create pads to connect the Velostat to the micro-controller.

Additional Electronics

Additional electronic components are often added to shape-changing composites to create effects that are not achievable with just the native qualities of the composite. Because of their changing shape, these composites make it hard to embed rigid PCBs. This leads to either manual wiring or the use of flexible printed circuits to connect the two parts of the system. Either way, a separate architecture has to be used to achieve the desired functionality. The Pyralux in the uniMorph composite can be used to easily embed surface mount components. Layout and routing of these components can be done with traditional tools like Eagle. This makes it simple to add components like LEDs or additional sensors. The precise fabrication method with solid ink printing allows for tiny footprints. We successfully used components with down to 8mil pitch and were able to create self-contained composites with microcontrollers, MOSFETs, and sensors embedded into the material.

The wiring of the electronics and placing of the components has to be done with the desired shape-change in mind. Components must not be placed on strongly bending areas and wiring should optimally not cross bending areas. Symmetric crossing prevents any negative effects on the bending behavior. Due to its relatively low heat resistance, the soldering of components should be done before adding the UHMW PE. Alternatively, conductive epoxy can be used to attach components to the material.

APPLICATION EXAMPLES

In the following section we show four applications that showcase different aspects of the presented uniMorph composite.

Flower Lamp Shade

passive bend actuation - The flower lampshade is a dynamic lampshade with the shape and analog behavior of a flower. Enchanted by its responsive materiality, the flower opens to distribute light instead of pollen (Figure 10). This artifact's shape-change is driven solely by the heat dissipated from the light bulb, exemplifying how unimorph structures can be used to inform us about ambient or local temperatures without the need of control circuits or power supplies on the material side. By imposing a lateral curvature onto the leaves with the holding structure, a drastic movement of the individual leaves is achieved, as the bending force has to overcome the holding force of the material similar to a bistable spring. With modern energy-efficient fluorescent or LED light bulbs, similar artifacts could be used to spatially dim light by shading it in different amplitudes using active uniMorph composites. The leaves of this artifact are composited of solely a layer of UHMW PE and black Kapton. The materials were composited in large sheets and then laser-cut into shape. A laser cut acrylic structure holds the leaves around the bulb.

Responsive Bookmark Light

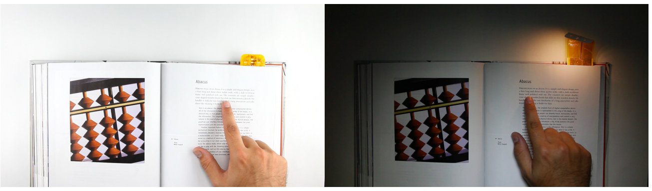


Figure 12. A responsive bookmark detects darkness and curls up to enable continued reading

active bend actuation, embedded SMD LEDs, Velostat foil sensing - This prototype doubles as a bookmark and a dynamic reading light. The bookmark automatically bends up and shines a light on the text when it becomes too dark to read (Figure 12). When the reader is done, simply sliding the light back into the book re-enables its use as a bookmark. The composite senses its new shape and turns off the light. This prototype exemplifies the ease of both embedding electrical components into the uniMorph composite and constructing embedded bend-sensing using Velostat® foil.

After the active sheet has been composited, as described earlier in the paper, the SMD components are soldered on carefully, in this case with a reflow heat tool. The Velostat is electrically insulated from the underlying copper wire with 0.3mil Kapton. To ensure a higher reliability, the Velostat is glued to the copper pads with a thin layer of conductive epoxy.

Post-it Notes

Figure 13. A board comprised of actuated post-its enables novel ways of browsing post-its

active curl actuation, capacitive touch sensing - The ubiquity of Post-It notes inspired several projects that digitally augment [25] or even physically actuate them [30]. In this example, we show a Post-It system that enables the notes to curl up individually in order to structure or order content (Figure 13). This function could be used in brainstorms to filter or group certain notes through curling. A timeline function could uncurl the post-its in the chronological order of creation. Animated motions can be designed as notifiers for notes of temporal importance (e.g. an upcoming deadline).

While the Post-Its are simple three layer composites as described earlier, the Post-It board controls the individual notes with a custom MOSFET Arduino board. Currently, categories have to be assigned manually but future versions could recognize them by more intelligent means like OCR.

Dynamic iPad Cover

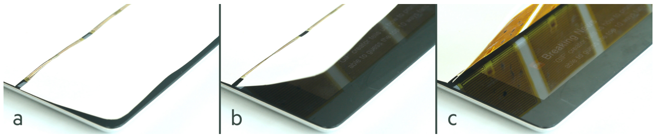


Figure 14. A dynamic iPad Cover notifies the user as well as offering improvised interactions

active fold actuation, capacitive bend sensing - Originally created as passive devices to protect tablet screens, tablet covers and their affordances have recently been explored as physical input devices by applications like Evernote®. In this application, we show a shape-changing iPad cover with the ability to inform and notify a user about the state of the iPad as a form of ambient media and also affords simple interactions. The iPad cover opens slightly when there is a notification waiting to be addressed by the user (Figure 14). While the opening angle can signify the amount of notifications, more urgent or specific messages can be displayed by specific movement patterns. Fast opening and closing might indicate a very urgent message, while a movement inspired by a heartbeat could signify a message sent from a loved one. The opening of the cover also creates a designed affordance for the user to open the cover completely. It also allows for more improvised interactions, like putting an object on top of the iPad cover to mute any kind of notifications.

The hinge is actuated by four identical modules in parallel. A strip of Velostat in each of the hinges informs the control circuit about the current angle of the cover, creating a closed driver loop while also detecting external interaction.

LIMITATION AND FUTURE WORK

The composite and fabrication process have some limitations and partially still require improvements. Further reducing the amount of manual work through automation as well as developing a more sophisticated bonding process would increase the success rates in fabrication and result in higher energy efficiency and force for shape-actuation. More efficient heat dissipation techniques would enable a faster reverse actuation. The biggest limitation of the current composite is the bending force. While the force is comparably strong for the thickness of the composite, it is not able to create strong haptic impressions or lift significant loads. Different material combinations might create a better trade-of between bending and created force.

Multiple Dynamic Properties

Driven by the vision of Radical Atoms [17], we strive for a group of dynamic materials that can represent and embody digital information. Gaining computational control of other material properties than shape is important for this mission. JamSheets [29] showed how controllable stiffness enables interesting physical HCI applications, while research like Kaiho and Wakita [18] showed the potential of color changing materials. Using plastics with a low thermal deposition temperature like polystyrene and thermochromic inks, we envision a more complex composite that would enable shape, stiffness, and color change thin sheet interfaces.

Scale

In this paper we presented thin shape-changing materials in small scale. Based on the mechanics explored in this research, there is an opportunity to apply the same mechanisms to different materials at larger scales. While stretchable materials and higher resolution fabrication methods could create micro-scale texture changes, working with bimetal structures might enable computer-mediated dynamic architectural scales [20].

Software aided design process

When designing shape-changing composites, an extensive understanding of the material behavior is needed. Usually this knowledge is acquired through manual experiments, resulting in constant oscillation between digital design and manual fabrication/evaluation. A tool that combines the insights of finite elements material simulations with digital design processes is needed speed up the digital design process and could lead to more complex form factors.

Conductive Ink and 3D Printing

Flexible printed circuit manufacturing with conductive inks has seen great progress in the last years and has been put to extensive use [38, 22]. While currently available inks are not able to withstand the load of resistive heating, we believe it is only a matter of time for this to be overcome. Directly printing circuits would remove most manual work from the prototyping process and lead to more rapid iterations. It would also allow for more specialized inks like force resistive or photo resistive inks to be employed easily into the material and add new functionalities. While commercially available multi-material 3D printers are not able to print conductive filament in combination with flexible materials, it is only a matter of time until an appropriate method for this will be developed. The uniMorph mechanism could be translated into more complex three-dimensional shapes that integrate not only electronic but also complex shape-changing capabilities.

CONCLUSION

This paper presents a thin-film shape-changing material as an architecture for simple prototyping of dynamic shape-changing artifacts and interfaces. The presented uniMorph composite enables passive and active shape-change with integrated control and sensing modalities. We fully document the fabrication methods needed to create uniMorph composites and show a collection of form primitives. We present techniques for touch and topology sensing and provide ways for embedding additional sensors and actuators into the composite. Furthermore, we provide quantitative performance data for bending behavior. Finally, we demonstrate the use of this composite for HCI in four applications.

This research serves as an enabling prototyping technique and inspiration for future explorations in thin shape-changing interfaces as well as an encouragement for more work in materially mediated human-computer interaction.

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