EpoMemory: Multi-state Shape Memory for Programmable Morphing Interfaces

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ABSTRACT

Smart shape-changing materials can be adapted to different usages, which have been leveraged for dynamic affordances and on-demand haptic feedback in HCI. However, the applicability of these materials is often bottlenecked by their complex fabrication and the challenge of programming localized and individually addressable responses. In this work, we propose a toolkit for designing and fabricating programmable morphing objects using off-the-shelf epoxies. Our method involves varying the crosslinker to epoxy resin ratio to control morphing temperatures from 40 °C to 90 °C, either across different regions of a shape memory device or across devices. Functional components (e.g., conductive fabric, magnetic particles) are also incorporated with the epoxy for sensing and active reconfiguration. A toolbox of fabrication methods and a primitive design library are introduced to support design ideation and programmable morphing. Finally, we demonstrate application examples, including morphing toys, a shape-changing input device, and an active window shutter.

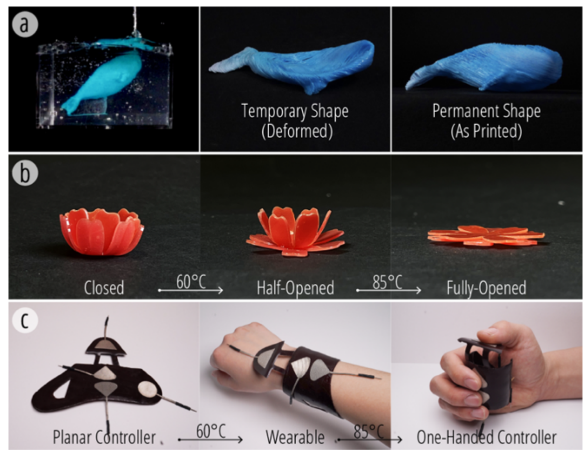

Figure 1: Application demonstrations. a) A morphing toy - a printed whale that can transform from a 2D shape to a 3D shape in a hot water bath; b) a two-layer flower that can unfold sequentially at 60 °C and 85 °C; c) a shape-changing input device with three modes: planar controller, wearable, and one-handed controller.

CCS CONCEPTS

• **Human-centered computing**; • **Human computer interaction (HCI)**; • **Interaction devices**;

KEYWORDS

Tangible interfaces, shape memory polymer, reconfigurable devices

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1 INTRODUCTION

Tangible media functions as a conduit between the physical realm and digital data. They present information through their shapes [30, 43], haptics [12], and dynamic behaviors [40]. Devices made of such media afford direct interaction with the human hand and can be more natural, intuitive, and ubiquitous. These affordances are further augmented by integrating shape-changing materials, such as shape-memory polymers [21, 36, 46], and digital fabrication. When exposed to certain stimuli (e.g., temperature, light, and pH), such smart materials can morph between pre-programmed shapes to display changing information or adapt their functions for a shift in the interaction context, thus enabling more dynamic interactions between the user, the device, and the information or program they embody. Shape-changing interfaces driven by smart materials can also be powerless [55], resistant to environmental factors [25], and be programmed to respond to different stimuli [18], thus enabling ubiquitous computing in unconventional contexts [29].

Despite the interaction opportunities suggested by shape-changing interfaces with smart materials, several design limitations including local activation (i.e., only specific parts of the material are activated/transformed) and the challenge to program sequential behaviors still bottleneck their practicality and versatility as an interaction media [35]. Existing methods utilized in an HCI context often use a single triggering condition (e.g., a prescribed temperature condition to trigger a self-folding [5, 47]) that limits localized and controlled deformation, and thus reconfigurable shapes that require sequential triggering. This lack of the ability to locally trigger different regions with programmable conditions limits the device's representativeness of information or functional adaptability for changing contexts. Outside of HCI, the engineering of multi-stimuli responsive materials has been an active research area. However, most of the solutions involve hazardous chemicals or highly involved synthesizing methods [15, 34, 51], which are not ideal for the HCI community to adopt.

Alternatively, shape memory polymers such as epoxy resins enable shape-changing transformations with off-the-shelf materials [23, 26]. Previous work has explored epoxy for morphing behaviors and artifacts, but their advantages, such as tunable crosslinker densities (i.e., the crosslinker to resin ratio) to achieve local and controllable (input stimuli/output deformation) has not been leveraged for designing interactive interfaces.

In this work, we propose a shape-changing interface prototyping method leveraging the advantages of epoxy to overcome these challenges of local activation and material programmability with digital fabrication for interactive devices. (Figure 1) Our method uses off-the-shelf epoxy for making shape-changing interfaces. By tuning the epoxy's crosslinker density (i.e., the crosslinker to resin ratio), the device can be programmed to initiate transformations at different, targeted activation temperatures between 40 °C to 90 °C. We explored the design space of epoxy with its shape memory ability (i.e., multi-state shapes and sequential transformation) and several structure primitives. A library of design primitives - from linear to volumetric elements - is also offered to showcase the design space. Furthermore, we introduce a toolkit for fabricating devices that combine multiple crosslinker ratios, enabling localized activation at different temperatures and temporal behavior programming. The toolkit includes several fabrication strategies (e.g., molding/casting, laser cutting, and embedded printing) and epoxy's functional composites from different particles for different functionalities (e.g., thermochromic, magnetic) to multi-layer structures with electronic elements (e.g., capacitive sensing, resistive heating). (Figure 2) Finally, application examples, including morphing toys (Figure 1a), a window shutter, and a shape-changing input device (Figure 1c), are presented to illustrate the enabled interaction design opportunities.

This method enables new dimensions of shape-changing interface design, and we introduce tools and means to fabricate such devices, as well as demonstrative design examples. This paper's contributions include:

1) A method for programming epoxy's activation temperature by controlling crosslinker:epoxy resin ratios for interactive devices.

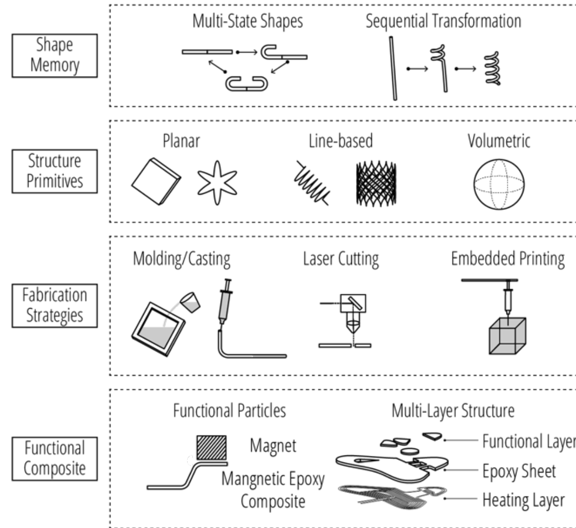

Figure 2: Overview of the design space and a toolkit of multi-state shape memory epoxy.

2) Strategies for fabricating devices that consist of varying temperature-responsive epoxy to produce multi-state shape-changing interfaces and a library of design primitives.
3) Examples of designs for multi-state shape-changing interfaces.

2 RELATED WORK

2.1 Shape-Changing Interfaces

Shape-changing interfaces are characterized by their ability to transform, and they provide affordances that are otherwise unattainable by their static counterparts [4]. Their applications range from communicating dynamic or spatial information [43], augmenting users [36], to context adaptive physical I/Os [31]. Most explored previous work has focused on two approaches: electrical and material-based methods. Electrical methods like LineFORM [31] used motors (electric actuators) and microprocessors to control shape changes. While electromagnetic motors are accessible (i.e., off-the-shelf availability) and ready to be integrated with other components for control, their rigid body poses limitations on more ubiquitous interfaces (i.e., challenging to integrate with soft, compliant, and customizable interfaces that can conform or adapt for safe interaction). On the other hand, smart materials (e.g., shape-memory polymer) can leverage digital fabrication tools to create customizable and transformative artifacts that respond to physical stimuli [47, 48]. Smart material devices are often made with additive manufacturing; the transformative behaviors can be controlled by changing local geometric feature or by tunning fabrication parameters (e.g., print speed [38], layer thickness [13], printing path [33]). In this case, personal fabrication machines like 3D printers are often used to create and program the transformative behaviors, making it possible for hobbyist makers to adopt. In HCI, smart materials are also accompanied by design tools that help users to model, program, and integrate them into their designs. As such, they provide advantages including lowered cost [5], ease to integrate additional I/O components [46], and the ability to morph onto existing users [36] and objects [39] for augmentation. Still, smart material devices often possess only two distinct shapes - before and after activation - and lack multi-state or temporal programmability. It is also challenging to program localized activation as the entire homogeneous device (made with the same material) would respond to the stimuli.

Situated among literature, our method provides a new paradigm: for local programmability, customizability in fabrication, and integration with other components for control (e.g., electronic parts) between existing archetypes. Our method leverages these advantages of the shape memory epoxy while enabling the feature of sustaining multiple stages (i.e., multi-state shape memory) without requiring constant external energy input. In particular, the multi-state programmability is reported to be underexplored in HCI [35] and can provide new interaction design opportunities. It is worth noting that the sparsity of shape-changing interface design and prototyping toolkits has been identified as a bottleneck for their dissemination [4]. While recent advances have provided computational [14, 54] and fabrication tools [7, 41, 49] for the community, there still remains a need to establish new physical media for different interaction affordances and scenarios. For this reason, we believe EpoMemory is a timely addition to the existing toolkits.

2.2 Reconfigurable Tangible Interface

Tangible interfaces enable the opportunity to interact with more than just one sense (e.g., touch, vision, sound), thus leveraging the full range of cognition and interaction. When augmented with reconfigurability, it can enhance interaction in applications like artificial reality [37, 50], gaming [19, 32], or haptic display [12, 40, 52] that require different I/O affordances for varying digital contents. To enable this feature, inForm [12] and ShapeBots [40] used a robotized assemblage (i.e., actuator pins matrix and swarm robots, respectively) that can self-organize to provide different interaction modes. While this method can provide virtually infinite configurations, their reconfigurability is afforded by an ensemble of actuators and electronics, requiring intensive assembly effort and programming controls as well as limited their interaction contexts (e.g., vulnerable to wetness). By contrast, EpoMemory takes a smart material-based approach. The reconfigurability is programmed through the fabrication process and embedded in the object themselves, thus reducing assembling efforts. When designed to leverage ambient heat for reconfiguration (i.e., without electronics), EpoMemory also extends reconfigurable tangible interfaces' applicable scenario (e.g., wet environments). On the other hand, there is also a lack of generalized design and fabrication framework for V/AR haptic devices. ElasiLink [50] and ElastiStick [37] aimed at creating V/AR haptic proxies that provide specific hand feel and gesture through adjustable mechanical parts (e.g., elastic bands), yet a generalized design and fabrication method is still lacking. This paper provides a method to fill this fabrication gap. Finally, when compared to other material-driven reconfiguration like self-healing UI [32], our method also takes advantage of the shape-memory effect and can transform without the human hand.

2.3 Material-Driven Multi-State Shape Change

Programming diverse transformation behaviors in materials have been a research hotspot both in and outside of HCI. Literature has explored various methods to create sequential shape-change. Among existing methods, tuning microstructures (e.g., porosity [42], film thickness [44], and actuator density [10, 28]) to control activation stimuli diffusion rates has become a common practice for timing local part responses. While such microstructures can be created, selective activation is still unattainable as the stimuli would eventually reach equilibrium within the entire device and cause all parts to transform. For this reason, other methods have explored using controlled, selective stimuli delivery for achieving local activation. Examples include using colored light to heat up correspondingly dyed regions [24] and using onboard circuits to heat up targeted regions [6, 11]. Nonetheless, such methods create certain limitations for appropriation in HCI; they often require active control and rely on specific apparatuses to deliver the activation stimuli, thus making it difficult to deploy the devices outside of lab space or for passive sensing-actuation interaction loops. Alternatively, it is also possible to compose or assemble different materials together to create localized responses [9, 27]. We leverage these works and propose a different approach by tuning the materials themselves to create localized responses, therefore simplifying the fabrication.

3 MATERIAL AND PROTOTYPING TOOLKIT

3.1 Background: Shape Memory in Epoxy

The shape memory effect refers to a material's ability to return to its original shape with applied stimuli. Epoxy as a thermally responsive polymer is one such example. When fabricated, the polymer network of epoxy remembers a prescribed shape (i.e., a fixed/locked shape), and the material is rigid and stable under room temperature. Yet, when exposed to heat above its glass transition temperature (T_g), the material becomes soft, rubbery, and deformable. In this state, the material can be deformed into a different shape by applied external forces, and when it is cooled below its T_g again, the material is temporarily locked in the deformed shape. At this time, the deformation stress and energy are stored in the polymer network. If the material is then heated above its T_g, the polymer network will release its stored energy and cause the material to transform back to its original shape.

3.2 Multi-State Shape Memory

Our contribution lies in the simple yet effective method of introducing multiple controllable glass transition temperatures to the same epoxy to achieve conditional and sequential control of multi-stable shape memory and reconfiguration. On a molecular scale, epoxy (a thermoset polymer) is composed of a network of monomers with crosslinkers as the connection nodes. The T_g of epoxy is directly related to the density of the nodes, which can be changed by modifying the ratio between the resin and the crosslinker. I.e., at a higher crosslink density, the polymer chains require more energy to recoil, resulting in a higher T_g, and vice versa. In this way, the T_g of epoxy can be tuned from 27 °C to 79 °C by changing the mixing ratio between the crosslinker (EPIKURE Curing Agent 3380, Hexion)

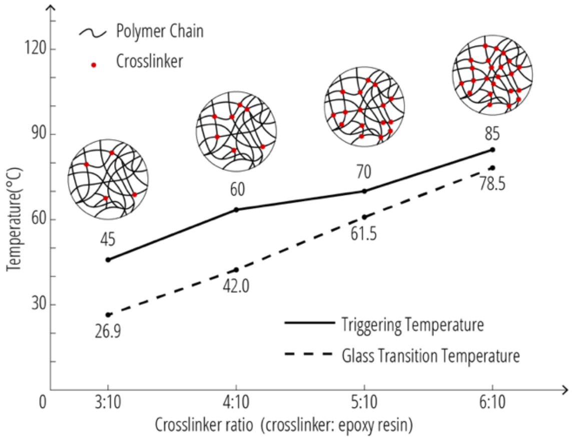

Figure 3: The glass transition temperatures and the triggering temperatures of shape memory epoxy can be tuned with different crosslinker:epoxy resin ratios.

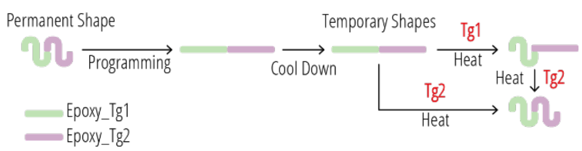

Figure 4: Multi-state shape memory achieved by integrating epoxies of different glass transition temperatures.

and the resin (EPON Resin 828, Hexion) from 3:10 to 6:10 (Figure 3), respectively. We leverage this property to create artifacts that afford multi-state shape memory by combining different crosslink densities; thus different T_gs, within the same object. As illustrated in Figure 4, for a sample consisting of epoxies with two T_gs (T_{g1}<T_{g2}), half of the sample can be triggered at T_{g1}, and the other half can be later triggered at T_{g2}. It is also possible to embed more than two T_gs in an artifact, and the resulting object will be able to carry out multi-state reconfigurations.

It is worth noting that when choosing the temperatures for reprogramming the shapes ($T_{Trigger}$), it is recommended to offset the temperatures to ensure the material is supplied with sufficient thermal energy for transformations (Figure 3). Theoretically, the shape memory effect will be readily activated with temperatures at or above T_g, but the time for transformation may vary (i.e., faster transformation at higher temperatures). The triggering temperatures marked in figure 3 are suggested empirically based on the material characterization and practical needs. Generally, we chose the lowest temperature for triggering when the characterized samples (described in Shape Memory Performance Section) can recover from a 90° bend within 10 seconds (Epoxy (3:10) is an exception with ~20 s activation time due to its reduced mechanical strength for shape recovery). However, temperatures lower than the suggested triggering temperatures (higher than T_g) can also be used for specific user cases (e.g., when transformation time is trivial but the lower temperature is highly desired).

4 INTERACTION THROUGH EPOXY

We further leverage epoxy's multi-state reprogrammability and inherent material properties to explore several design opportunities enabled by our method. The ability to program localized responses allows us to create objects that can locally and/or sequentially transform. Using epoxy as the backbone material for shape-changing interfaces also enables the possibility to integrate functional components into the devices to provide additional I/O features. The directions we explore include:

4.1 Reconfigurable Shape and Function

Shape-changing interfaces can come in different form factors - from lines, sheets, to volumetric shapes. We demonstrate primitive structures in all these categories and their enabled programmability and reconfigurability. Specifically, the sequential transformation enables complex behaviors and functions like self-tying knots, and the localized actuation can be used to create devices that can adapt their shape in different ways depending on the interaction context, such as a shape-changing input device. In addition, epoxy is also deformable in its hot state and can retain its shape when cooled down. We leverage this property to create conformable wearable interfaces. It is also worth noting that each type of structure also requires a different fabrication approach, and we leverage this versatility in methods by providing a prototyping toolkit.

4.2 Additional Activation Methods Beyond Ambient Heat

While we can achieve multi-state shape memory by tuning the glass transition temperature, our material system is also compatible with other triggering conditions such as electricity and light triggers. We take inspiration from the literature [6, 10, 24] to demonstrate that EpoMemory can be activated with different types of activation methods and beyond. With uniform heating, sequential triggering can be realized by our method of distinct T_gs (Figure 5a), or photothermal responses from different colors (Figure 5b). Additionally, multiple circuitries can be employed for local heating (Figure 5c). These delivery methods each has unique applicable scenarios. For instance, a multi-state responsive device can be used for temperature sensing in environments that are sensitive to high temperatures (i.e., 45 °C to 85 °C) (Figure 5a). Together with dyes, IR heat lamps can provide controlled and untethered heat delivery for single (Figure 5b) or multiple devices. Similarly, onboard circuits can be used to achieve partial activation with a homogeneous material (Figure 5c).

5 STRUCTURE AND FUNCTION PRIMITIVES

5.1 Synthesis of Epoxy

To fabricate epoxy, the resin (Hexion EPON resin 828, polymerized) and crosslinker (Epikure 3380) are mixed with a planetary centrifugal mixer (Thinky AR-100) for three minutes and defoamed for another three to remove trapped air. At this point, the mixture becomes thick and has a pot life of thirty minutes for fabrication. The fabricated epoxy is left at room temperature to gel for 24 hours before curing in a 100 °C oven for 5 hours. Depending on the target geometry and form factor, different fabrication strategies are

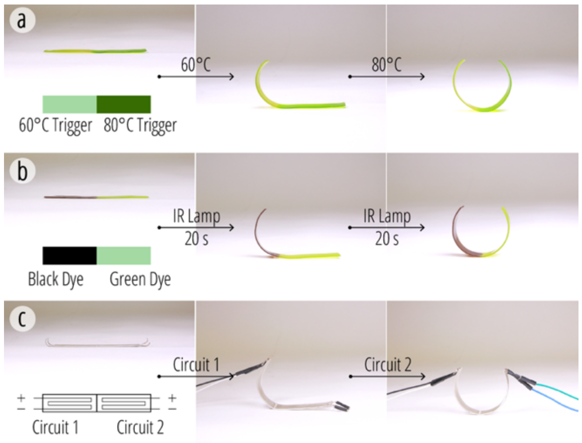

Figure 5: Multi-state shape memory with epoxy activated by different methods: a) distinct activation T_gs, b) photothermal responses, and c) local heating.

employed for different structural primitives, and they each have unique advantages. For example, planar and line-based structures can be straightforwardly molded and cast, while 3D printing is favorable for prototyping hollow structures and complex shapes.

5.2 Planar Primitives

Folding and unfolding enable large deformation or motion, inducing the transformation between 2D templates and 3D structures. Depending on the molded initial shape, the sheet made of epoxy can be programmed to either fold or unfold when activated (Figure 6a). To begin, the resin and crosslinker mixture is cast into a sheeting mold. Once the mixture has gelled, the sheet will become solid yet compliant and deformable by hand. At this state, the sheet can be programmed (deformed) into a 3D shape, and the 3D shape will become its default configuration. If the programmed 3D structure is flattened, it can self-fold back to the 3D default shape when heated. A benefit of this fabrication strategy is the programmability of 3D permanent shapes after gelation (i.e., when liquid epoxy solidifies) and before curing; the sheet can be manipulated (e.g., flattened, folded) to alter their programmed shape. It expands the design space of shape-changing interfaces with 3D structures, avoids the preparation of complicated molds, and reduces fabrication complexity. Alternatively, the epoxy can also be cured as a planar sheet. In this case, the sheet can be laser cut into desired shapes, and if the sheet is deformed into a 3D shape, it will be able to unfold and become flat.

The casted sheets can be composited to create multi-state devices with sequential transformation. Here, the sequential unfolding of a two-layer flower is demonstrated. The flower was fabricated by assembling two laser-cut epoxy sheets. The sheets are joined together by adhesives, and the outer (4:10) and inner (6:10) layers have activation temperatures of 60 °C and 85 °C, respectively. Figure 6b shows the sequential unfolding motions of the flower when heating from room temperature to 60 °C first and then to 85 °C in hot water baths.

5.3 Line-based Primitives

Line-based structures can achieve a locking mechanism with sequential motion. In this case, a self-tying knot is prototyped with epoxies of three crosslinker:epoxy resin ratios from 4:10, 5:10, to 6:10. The epoxies are indicated in gray, pink, and red in Figure 7a, respectively. A commercially available silicone tube (Uxcell, ID = 1.5 mm) is used for molding and is removed after the epoxies are cured. The flexible silicone tube mold can be manually tied into the desired shape. When cured in the tied silicone tubes, the epoxy will be programmed with the initial knot as its permanent shape. To demonstrate the self-tying/locking mechanism, the knot is first manually untied in a hot water bath and cooled to room temperature to retain the temporary straight shape (Figure 7b). The straightened line is then placed in a 60 °C (Figure 8a) water bath and gradually heated to 70 °C (Figure 8b) and 85 °C (Figure 8c) to complete the knot. In this locking process, multi-state shape memory is essential because sequential motions are required to avoid self-collisions, and the knot needs to be completed in a specific transformation order.

5.4 Volumetric Primitives

To demonstrate volumetric primitives, a bunny is molded with a silicone mold (Ecoflex 00-30, Smooth-on). As shown in Figure 9a, the bunny's ears are cast with epoxy of a 4:10 crosslinker ratio and indicated in pink, whereas the body is cast with epoxy of a 6:10 ratio and indicated in blue. The activation temperature difference makes it possible to transform the ear without activating the body. As shown in Figure 9b, the ears can be deformed and locked in a curved shape and recover to the original configuration when heated to 60 °C.

Noticeably, for volumetric structures, epoxy's shape memory effect is more applicable for a hollow structure or shell structure than a solid one. Since epoxy is a relatively stiff polymer, the deformability is limited as the thickness of the material increases, resulting in less prominent shape changes for solid structures. Additionally, it is also challenging to heat throughout the solid structure uniformly, restraining the shape recovery performance. Therefore, we use 3D printing to fabricate epoxy into shell structures. Unlike conventional 3D printing materials that are thermoplastic, uncured epoxy is liquid and does not melt after curing, thus cannot be printed by fused deposition modeling (FDM). Instead, we use embedded printing [2] to sustain the uncured epoxy's shape while it is curing. A support bath made of 1% w/v Carbopol is used in this process, and the epoxy was extruded into the bath with a direct ink writing printer (Hyrel System 30M) into the desired shape (Figure 10a). We refer to [53] for details on preparing the support bath with Carbopol. The bath functions as all-directional support to sustain the epoxy's shape before it is cured, and the support materials can be washed away with water to release the cured object. Figure10b shows a printed spherical shell, which after curing, can be taken out of Carbopol and demonstrate volumetric shape changes.

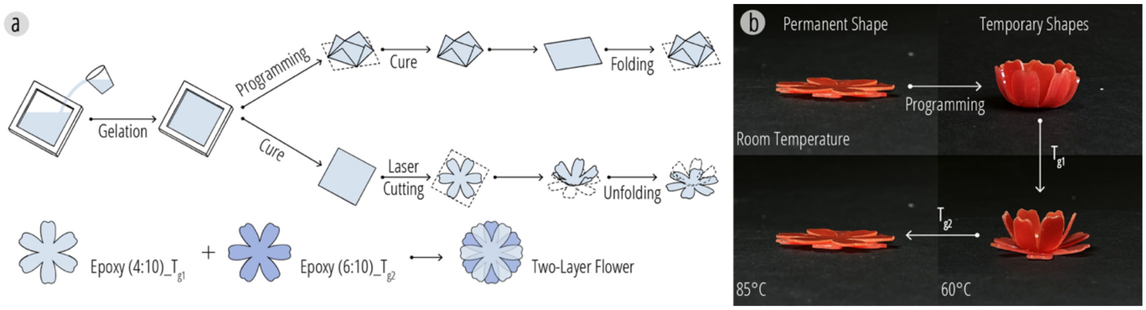

Figure 6: Planar primitives for sequential folding/unfolding. a) Schematic fabrication process of the planar primitives; b) a multi-layer flower that can unfold sequentially at different activation temperatures.

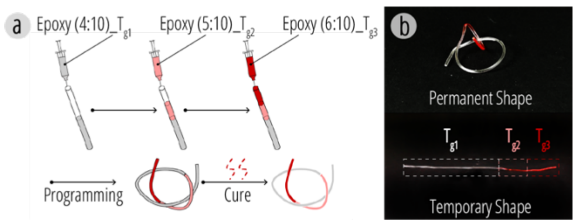

Figure 7: Fabrication of a self-tying knot. a) Epoxies with different crosslinker:epoxy resin ratios molded in silicone tubes; b) the permanent (top) and temporary shape (bottom) of the knot.

6 FUNCTIONAL COMPOSITES

6.1 Magnetic Epoxy Composite

Magnetic particles have been incorporated into a polymer matrix to create various functions, including untethered control of shape change [56], tunable mechanical properties [17], and more [16, 22]. We explore integrating magnetic particles into the shape-memory epoxy to induce magnetic responsiveness. Neodymium–iron–boron (NdFeB) magnetic particles (d=5 μm) are mixed in epoxy and molded into a stripe (Figure 11a). As illustrated in Figure 11b, the composite is rigid under room temperature and does not deform with external magnetic fields. Yet, when the epoxy is heated, the stripe becomes soft and is bendable by a permanent magnet. The stripe can be locked in its deformed shape by cooling below its T_g. By incorporating functional magnetic particles, we can control temporary shape changes at relatively high temperatures without requiring manual manipulation.

6.2 Thermochromic Epoxy Composite

Epoxy by itself can be made with different colors by adding dyes (e.g., food dye). Yet, it is also possible to program color change - in addition to shape change - in response to heat. This is achieved by adding thermochromic dyes that have an activation temperature between room temperature and epoxy's T_g . The thermochromic dyes were added to the epoxy along with the crosslinker. Figure 12 shows a sample that can change its color from pink to yellow at 31 °C.

6.3 Epoxy with Capacitive Sensing

In addition to additive particles, the epoxy can also be composited with onboard circuits for sensing. In this case (Figure 13), a conductive fabric (Adafruit, Woven Conductive Fabric) was laser cut into four patches as capacitance sensing buttons, and the circuit was attached to the epoxy sheet using adhesive tapes (3M, VHB tape). The assembled device can be used as both a gamepad when flat (Figure 13b) or as a wearable computing interface (Figure 13c) when wrapped around the human body. Specifically, when the epoxy is heated, the fabric patches can deform along with the epoxy sheet and conform around an object.

6.4 Epoxy with Resistive Heating

A heat source is required to activate epoxy's thermal-response and the interfaces' morphing behaviors. Most prototype examples shown in previous sections used external heating methods like hot water baths (knots in Figure 8) and heat guns (bunny in Figure 9). However, it is difficult to maintain uniform heating with a heat gun and a hot water bath may not be applicable for scenarios where wetness should be avoided (e.g., in the presence of electronics, fabric, or water-soluble materials). Ovens can be an alternative, but the heating method would be limited to lab spaces. Therefore, resistive heating elements including commercial heating pads, copper traces, conductive inks, and conductive fillers can be introduced for flexibility and portability. Commercial heating pads are a convenient choice, while copper traces are more customizable when it comes to irregular shapes or complex designs. Conductive inks can be flexible and conformable to a shape memory epoxy device during shape transformations. All three above-mentioned elements need to be externally applied on or laminated between epoxies. On the other hand, conductive fillers (e.g., carbon black, carbon nanotubes, sliver flakes) can be used in epoxy composites to create electrical conductivity for resistive heating, which is expected to enable more effective and uniform heating throughout the material and have less structural complexity without delamination issues.

7 APPLICATIONS

7.1 Morphing Toys

Leveraging the shape memory effect, we made three interactive toys with epoxy: a whale, a letter toy, and an octopus. The toys are fabricated with the embedded printing method and the printed

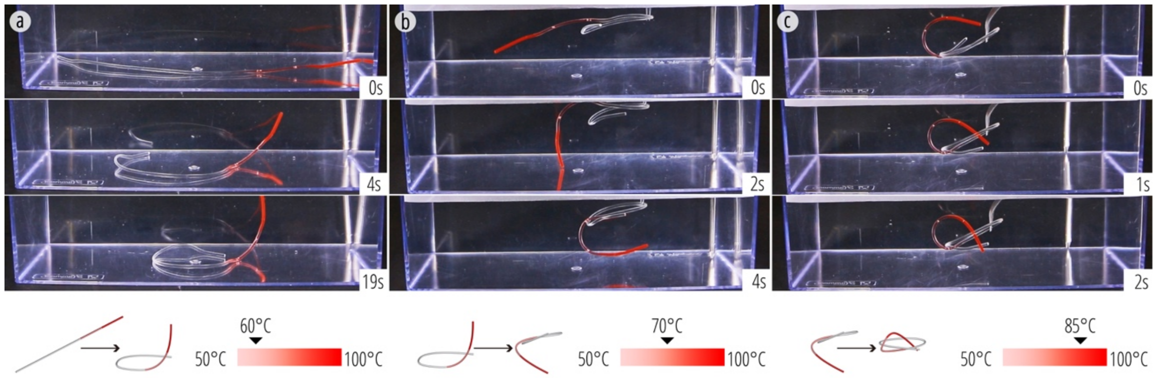

Figure 8: Multi-state shape memory of the self-tying knot. The transformations of different parts in a) 60 °C, b) 70 °C, and c) 85 °C water baths.

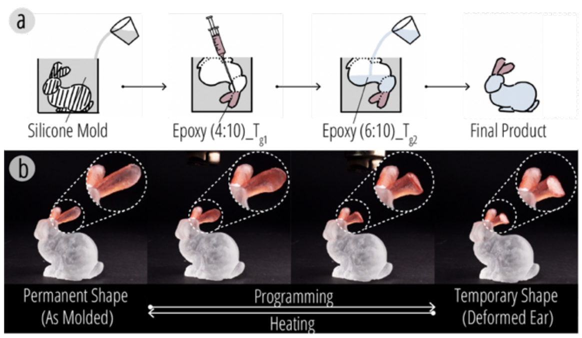

Figure 9: Fabricating volumetric primitives by molding. a) Schematic illustration of the bunny's molding steps; b) the bunny's ear can be deformed and recovered at T_{g1}.

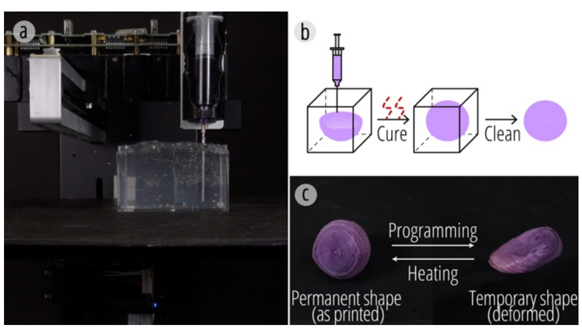

Figure 10: Fabricating volumetric shell primitives: (a) the ink writing printer (Hyrel) for embedded printing; (b) the schematics of the printing process and (b) a printed hollow sphere that can self-recover when deformed.

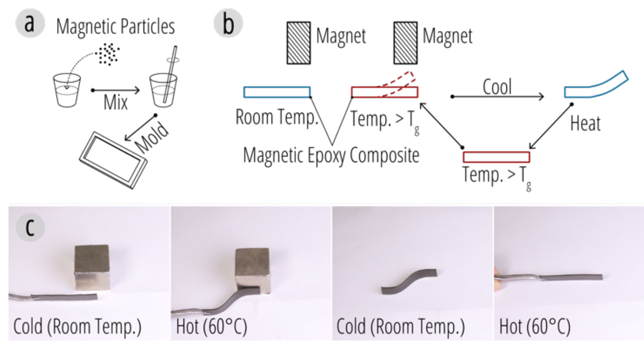

Figure 11: Magnetic particle-epoxy composite. Schematic illustration of a) the fabrication process and b) the untethered control of shape changes by permanent magnets; c) Magnetic epoxy composite sample deforms until it is heated, and the deformed shape can be locked at room temperature and recover to permanent shape upon heating.

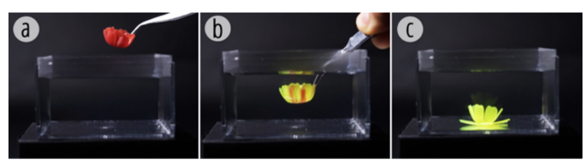

Figure 12: A two-layer flower changes color from a) pink to b) yellow when put in 60 °C hot water c) with the outer layer activated.

shape was programmed as their permanent default state. The toys can be deformed or manipulated into different shape-states and recover to their printed shape when placed in a hot water bath without external loads. Figure 14b shows the fabrication of the whale. The permanent shape is defined by curing the whale as printed (Figure 14a). The whale can be deformed when exposed to heat above the epoxy's T_g (60 °C) and locked into a temporary shape upon cooling (Figure 15a). This approach also allows users to encode messages that are only visible under specific conditions (i.e., >60 °C heat, Figure 15b). An example is the letter toy, which was printed as 'CHI' and deformed (i.e., encrypted) manually into a random shape where the original letters were not recognizable. Figure 16 shows the snapshots of the letter toy's recovery process

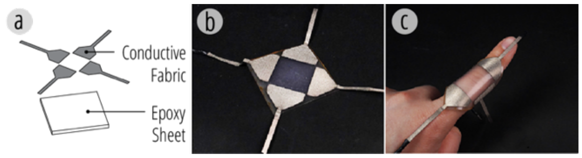

Figure 13: Epoxy with conductive fabric for capacitive sensing. a) Schematic illustration of the sensing pad; photos of the device with sensing pads b) in a planar shape and c) when transformed into a finger wearable.

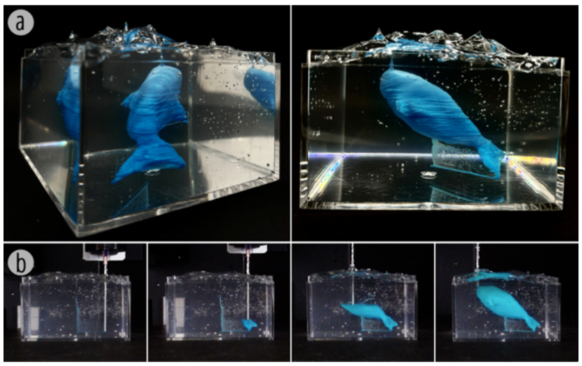

Figure 14: Fabrication of the morphing whale toy: a) The printed whale and b) the embedded printing process.

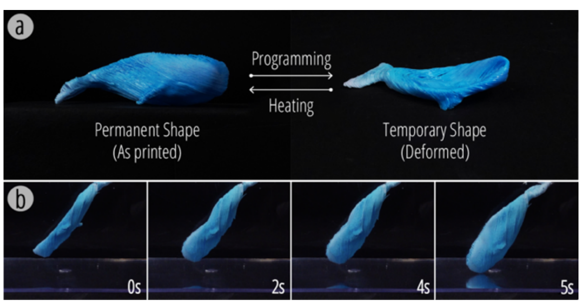

Figure 15: The morphing behavior of the toy whale: a) the whale's permanent and temporary shapes and b) shape recovery in a 60 °C water bath.

when put in a hot water bath (60 °C), demonstrating the encoded message that can be defined by a user.

On the other hand, the multi-state shape memory feature can also be used to produce interactive toys. In Figure 17, the octopus's head and the tentacles are printed separately with different crosslinker ratios (4:10 and 6:10, respectively). The cured parts are then assembled with adhesives and can be deformed in the same manner as the whale. Yet, in a 60 °C-water bath, only the octopus's head is activated and recovered (Figure 18a), and the tentacles are only responsive to water temperatures above 85 °C (Figure 18b). Such designs can be used as a visual sensor (e.g., by observing the toy's recovery and deformations, we can determine the bath's temperature without relying on a thermometer reading).

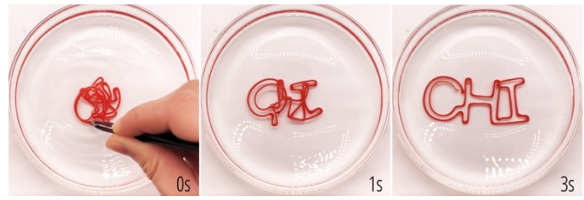

Figure 16: Shape recovery of the letter toy in a 60 °C water bath.

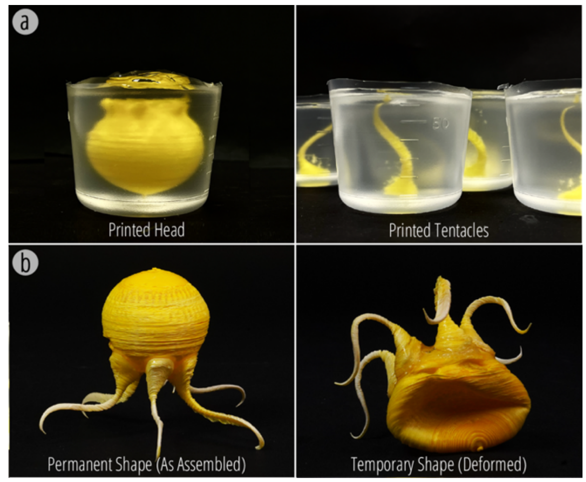

Figure 17: The morphing octopus. a) The embedded printed head and tentacles of the octopus; b) the permanent and temporary shape of the octopus.

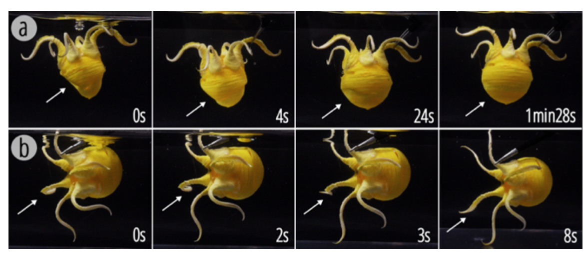

Figure 18: Sequential morphing of the octopus a) in 60 °C hot water with the head recovering to its permanent shape and b) the tentacles uncoiling in 80 °C hot water.

7.2 Shape-Changing Input Device

We prototyped an input device that can change shape between three functional modes. Figure 19 illustrates the device's design schematics, which consists of two parts made with different crosslinker ratios. The device's first mode is a planar controller with four buttons integrated for capacitive sensing. When heated to the activation temperature of 60 °C, only the corresponding part will transform, and the device will become a wearable controller that conforms to the forearm and hand (Figure 20b). The current prototype was fabricated through a molding process. We defined and printed a support to hold the prescribed shape (Figure 21(c), the one-handed

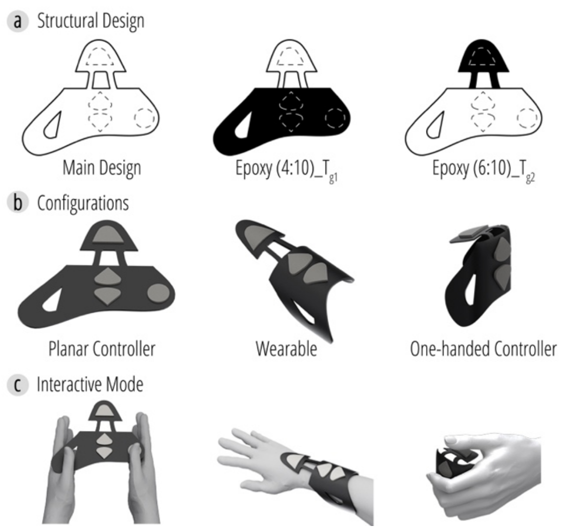

Figure 19: Design of the shape-changing input device. a) Structural design: two-part design with epoxies (4:10 and 6:10); rendered 3D models b) configurations and c) interactive modes.

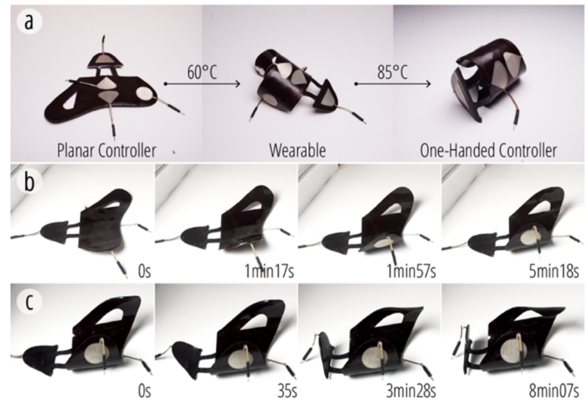

Figure 20: Fabricated shape-changing input device a) in three modes: planar, wearable, and one-handed controller (from left to right). b) The device’s transformation from planar to the wearable controller and c) from the wearable to the one-handed controller.

controller) during the curing process. As we discussed earlier in section 5.2, the shape can be programmed after the mixture of resin and crosslinker is gelled into a solid but deformable state. The shape of the wearable is determined by the permanent shape defined during the fabrication process. Yet, one can manually adjust its fit above 42 °C to provide better customizability. In this case, heat insulation is recommended for safety. If we heat the device further to 85 °C, the top part can be activated and transformed into the third mode, a one-handed controller (Figure 20c). The controller provides three sensing buttons when held in the user’s hand. Figure 21 shows the capacitive sensing buttons’ function under the three different modes. Note that there is no heat insulation in this demonstration because we used an oven to trigger the shape change and waited until the device was cooled down to wear. However, resistive heating elements can be integrated for on-body reconfiguration in the future, and a heat insulation layer (e.g., fabric) will be needed.

7.3 Interactive Window Shutter

The epoxy composite can also be used to make everyday objects more interactive. We create an interactive window shutter consisting of an array of magnetic composite stripes. The units are designed with a flat permanent shape, so the shutter is closed by default. The units’ opening and closing are controlled by a magnetic glove. This glove functions as both the magnetic stimuli and heat insulation. Heat insulation should be taken into consideration when choosing a glove for this interactive window. The glove is embedded with permanent magnets that can attract heated units toward them (Figure 22a). Magnets with different sizes and shapes can be integrated either inside or outside of the gloves (e.g., finger-size magnetic plates can be bonded inside or outside). Depending on how the user waves their hand above the shutter, selected units can be triggered and opened to varying patterns and allow different amounts of light to shine in. As a proof of concept, four shutter units are fabricated with a 4:10 crosslinker ratio using the sheet fabrication method. The prototype was deformed with a magnetic glove when heated above 60 °C and then maintained the opened state by cooling (Figure 22c). Note this prototype needs a relatively long cooling time (30 – 60 s), which means the user who attempts to reprogram the shape states of the shutter must hold the hand in front to the target shutter units for at least half a minute. The duration required may vary depending on the environmental condition, for example, in a colder winter, it may take much shorter time to fix the shape.

More functionalities are enabled by the multi-state shape memory feature of the composite. Figure 23a demonstrates a window shutter unit with two modes. The unit is made of two epoxies with magnetic particles, of which the lower part will be activated at 60 °C, and the upper part will be activated at 85 °C. At room temperature, the shutter cannot be opened by magnetic actuation due to epoxy’s high stiffness.

If we provide a lower power (4.28 W) to heat the unit to 60 °C, half of the unit will be activated and primed for deformation. Therefore, the shutter can be half-opened when the magnetic glove comes close to the units and the half-opened state can be cooled as a temporary shape. Once the unit is heated above 60 °C again, the shutter will automatically unfold back to its flat permanent shape to close the shutter (Figure 23b). Alternatively, if we pump in a higher power (6.33 W) with the same heater to bring the unit to 85 °C, the entire unit becomes deformable. In this state, we can open the shutter units to a larger angle. The fully opened shape can also be locked when cooled down and be closed with the control of a power supply (Figure 23c).

8 SAFETY

8.1 Material Handling and Fabrication

We believe the material and methods described in this paper can be safely adopted by designers and makers who have limited experience synthesizing chemicals in the past. Here we share some

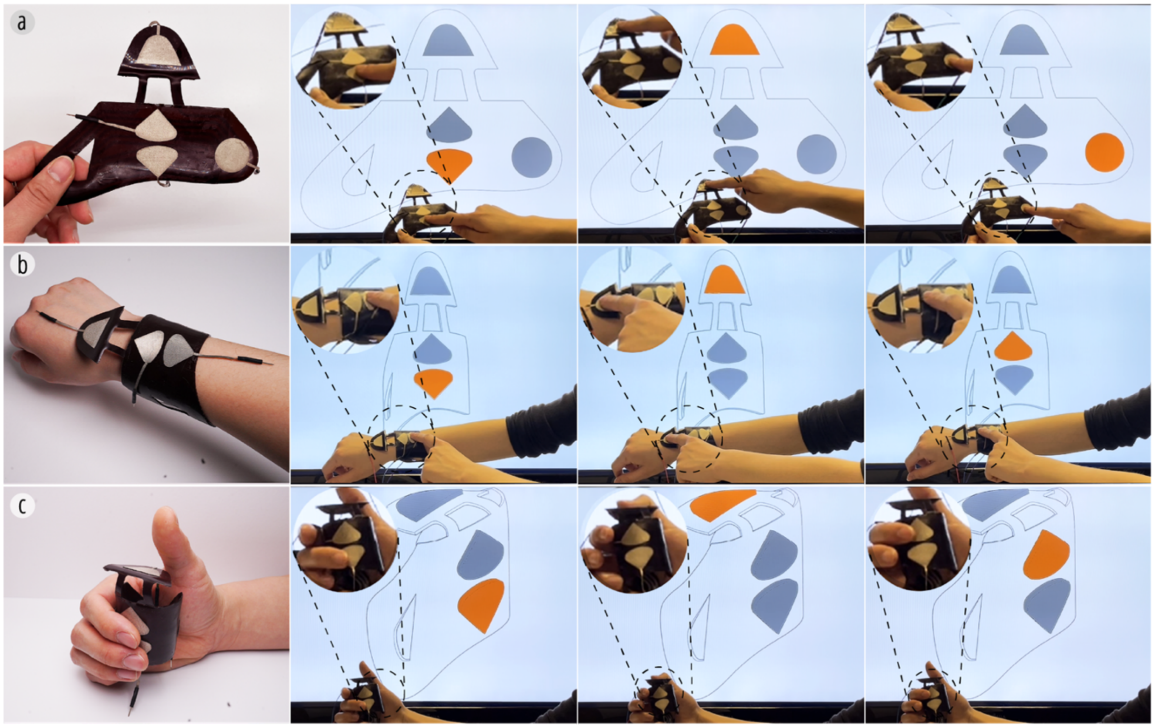

Figure 21: Demonstration of the input device in different modes: a) planar, b) wearable, and c) one-handed controller.

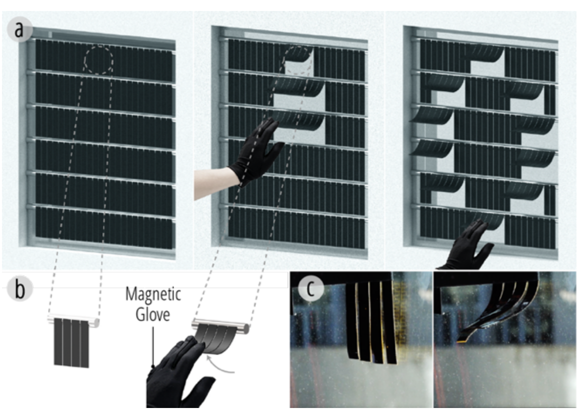

Figure 22: Interactive window shutter demonstrated with a four-unit prototype: a) model of the entire window shutter and the b) four units. c) Prototypes of the four units.

basic safety handling instructions and articulate the safety factor of the devices after curing.

Fabrication Phase. The shape memory epoxy consists of the resin (Epon 828) and the curing agent (Epikure 3380), which are toxic to the human body before curing. Therefore, personal protective equipment (i.e., nitrile gloves) and adequate ventilation are required for safe handling during the fabrication process. We recommend handling epoxy at well-ventilated spaces like fume hood, painting booths, or around a fume extractor. We note that epoxy resins and curing agents with similar chemical compositions are also present in commonly used commercial products (e.g., Gorilla epoxy glue), so they should be safe to use given proper personal protection and handling practice.

Post-curing Phase. After curing, even with different crosslinker ratios as suggested in our work, the materials are safe in contact with skin. The resin we use (Epon 828) is made by the reaction of epichlorohydrin with bisphenol A (BPA). According to the material company (Hexion, Inc.), the estimated amount of residual BPA is less than 1 part per million (1 ppm) in Epon 828. Moreover, residual BPA will also react with the curing agent and be further reduced after curing. In practice, if one uses 100 g of the epoxy resin (for our wearable input device – the largest prototype in this work – used 12 g, by comparison), the maximum possible BPA exposure should be much less than 0.1 mg. Both Food and Drug Administration (FDA) and European Food Safety Authority (EFSA) have determined the no-observed-adverse-effect level (NOAEL) of BPA for systemic toxicity to be 5 mg/kg per body weight per day [1, 8] (For a 50 kg person, the NOAEL of BPA is 250 mg per day). Still, even though it is safe for the skin, we do not recommend using epoxy for applications that involve contact with food based on low-dose BPA ingestion studies [20].

8.2 Wearable Context

For wearable applications, a protection layer (e.g., fabric) is highly recommended when the material is used in contact with the skin, especially for persons with skin sensitization problems. On the other hand, epoxy requires a triggering temperature above 45 °C, so

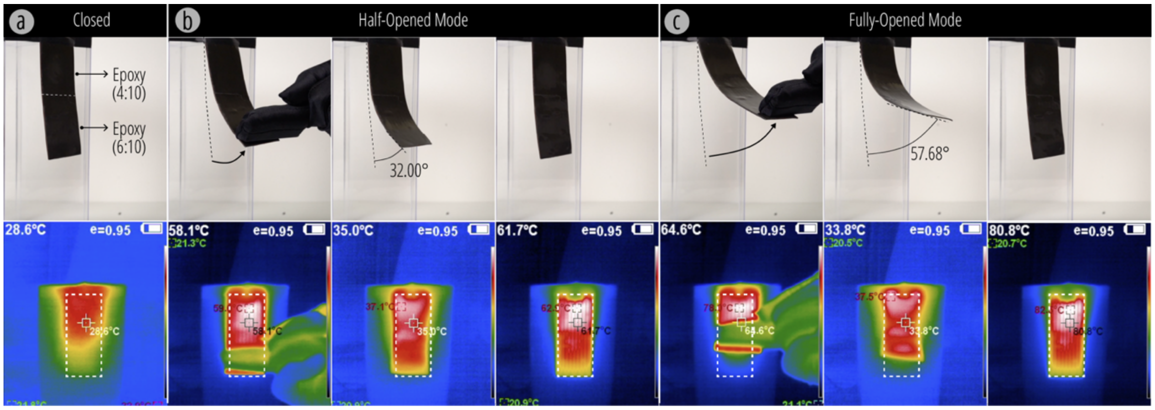

Figure 23: A unit of the interactive window shutter between different modes: a) closed state, b) half-opened at 60 °C, and c) fully opened at 80 °C.

the users should take off the wearables during the trigging process to avoid injury. In the future, on-body reconfiguration can be realized by integrating resistive heating elements and heat insulation designs.

9 MECHANICAL AND MATERIAL CHARACTERIZATION

9.1 Shape Memory Performance

The epoxy's shape memory performances are evaluated from three aspects: 1) activation time, 2) shape reconfigurability range, and 3) repeatability of shape reconfiguration. Strip epoxy samples (crosslinker ratios: 3:10, 4:10, 5:10, and 6:10) were manually deformed to targeted bending angles (temporary shapes) and the shape memory effect was triggered under different temperatures. We note that the activation time significantly depends on the geometry (e.g., thickness) due to heat diffusion, thus it should be calibrated according to the use case. Based on our prototypes, we measured the activation time of 2 mm thick samples under different deformation angles (30°, 60°, 90°), triggering temperatures (45, 60, 75, 90 °C), and crosslinker ratios (3:10 - 6:10). Hereinafter, we add the crosslinker:epoxy resin ratio in parenthesis, e.g., epoxy with crosslinker: epoxy resin of 4:10 is designated as epoxy (4:10).

The main findings from the shape memory characterization are summarized as follows. The epoxy's shape recovers faster at smaller deformations and higher temperatures, and epoxy recovers faster with lower crosslinker ratios (e.g., epoxy (4:10) is faster than epoxy (6:10)) under the same testing temperature. These should be considered when a targeted response time or frequency is required for a morphing interface. Besides, for the reconfigurability, all strip epoxy samples show recovery rates above 99% with a maximum bending angle of 180°, and the recovery rates remain above 96% after 20 cycles of 90° bending. The high recovery rates and cyclability ensures that the devices can transform repeatedly between programmed and deformed shapes without losing its function. However, we acknowledge that device repeatability in real world scenarios (i.e., where thousands and more cycles are needed) may require further validation.

Figure 24 (a) through (d) shows epoxy's recovery time with respect to deformation angle and triggering temperature. For each triggering temperature, only samples (crosslinker ratios) with a T_g lower than the triggering condition were tested. The activation time ranges from 1 to 20 seconds across all samples. Under the same testing temperature (Figure 24 (d)), the activation time increases with a higher crosslinker ratio due to higher crosslinking density and less flexible polymer network. For the same crosslinker ratio (e.g., 3:10), the activation time increases with larger deformation angles and decreases with higher triggering temperatures. Specifically, the activation time decreases by one order of magnitude when the temperature increased from 45 °C to 90 °C. These parameters can guide the design for targeted performances (e.g., response time, frequency), and they should be considered when design for specific application contexts.

Next, we quantify the shape reconfigurability (deformation) range of epoxy strip samples by measuring the recovery at different deformation angles. The shape recovery was calculated by dividing the recovered angle to the deformed angle. The epoxies' shape recovery in the first shape memory cycle is shown in Figure 24 (e). All samples had recovered above 99% even for a 180° bending deformation. An additional tensile test in a load cell (Instron 5969, 1kN) also suggested that epoxy remains elastic up to a 30% strain at 60 °C, and the samples and prototypes should, in theory, be able to recover to their permanent shapes within this range of deformation. Finally, we bent the samples to 90° for 20 times and measured the mean shape recovery to examine their repeatability of shape reconfiguration. As shown in Figure 24 (f), the shape recovery rate remained above 96% after 20 loading cycles for all four crosslinker ratios.

9.2 Delamination

The interface between two consecutively casted epoxies (e.g., the casting method illustrated in Figure 6a) may appear susceptible to delamination when subjected to tensile loads. However, the connection is in fact robust as the polymer networks are linked by chemical bonds formed during the curing process. Figure 25 shows an experiment to validate this property. Four bar samples made with

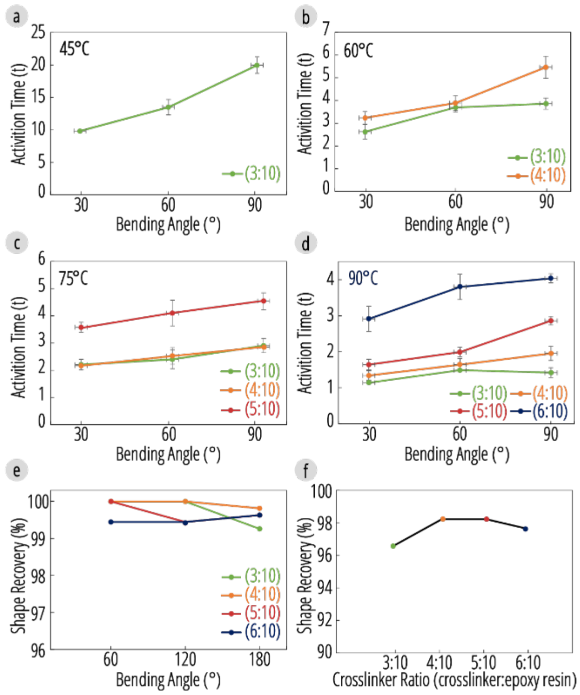

Figure 24: The shape memory performance of the epoxies: (a) - (d) activation time; (e) shape reconfigurability range; (f) repeatability of shape reconfiguration.

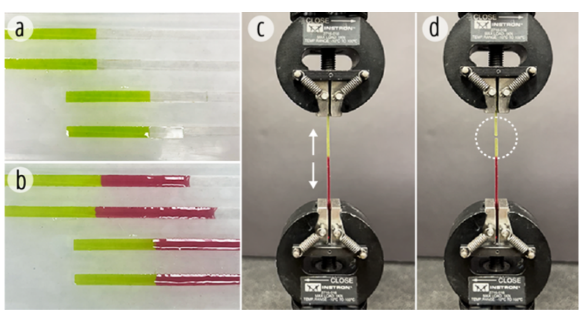

Figure 25: Testing the interface between epoxies with different crosslinker:epoxy resin ratios. The samples consist of a) a green (4:10) and b) a purple portion (6:10). c) Images of the tensile test conducted on a universal testing machine and d) the sample does not break at the interface.

two epoxies were cast in a silicone mold; the two epoxies were cast five hours apart and cured as a whole. The cured samples are then pulled on a universal testing machine (Instron 5969) until break to verify the interface's strength. Anecdotally, we report that none of the samples broke at the interface between the two epoxies when about 32 MPa of stress (~200 N for a sample with a cross-sectional area of 6.24 mm^2) is applied during the tensile test.

10 DISCUSSION AND LIMITATIONS

10.1 Shape Design Space and Thermal Management

Epoxy can be easily shaped into one to three dimensional elements or objects for making devices. Yet, their geometric design space is governed by the stimuli - heat. In general, thin or slender geometries are quicker to heat up and attain a uniform temperature across the device than thick ones. By contrast, solid volumetric shapes have a higher thermal capacity with respect to surface area and may require more time to heat up. Thicker devices are susceptible to temperature gradients between its inside and outside, leading to imprecise heat control. However, it is possible to overcome this issue by using embedded heating and cooling elements in a solid volumetric shape. Similar to heating, the cooling time is also affected by device dimensions and triggering temperature. A thicker device would also require more time to dissipate the heat, and it may take a relatively long time to cool the device than to heat it. For example, the magnetic epoxy units in the window shutter demo take ~10 s to heat up but require 30 s-60 s to cool down and fix their shapes. In the future, thermal conductors or active cooling elements can be used to decrease its cooling time.

Furthermore, a design tool can be developed for EpoMemory as part of future work. Sequential shape transformations can be complicated if the epoxies' different mechanical properties are taken into consideration. For example, range of deformation varies for epoxies with different crosslinker ratios, so it is important to consider the material's mechanical properties and identify feasible shape transformations when designing a shape-changing device. Therefore, the morphing behaviors and deformation strain can be simulated by the design tool to provide guidance to users. Besides, simulations on the heating and cooling processes, which is a diffusion problem, can provide users with a prediction on the response time and expected cooling time, as well as visualizing sequential transformations.

10.2 Device Prototyping and Fabrication

The attainable triggering temperature, ranging from 27 °C to 79 °C, can be controlled by tuning the crosslinker:epoxy resin ratio from 3:10 to 6:10. The range is bounded by two factors: the upper limit is determined by the stoichiometric ratio (exact ratio at which complete chemical reaction takes place) of the functional groups in the resin and the crosslinker. That is, the crosslink density will not increase beyond the stoichiometric ratio even when more crosslinker is added due to the saturation of chemical reaction. Similarly, while lower crosslinker ratio leads to reduced T_g, the resulting epoxy's mechanical strength will also decrease with reduced crosslinking density. Moreover, if the T_g of epoxy (3:10) becomes lower than the room temperature, it creates a challenge in device control. Therefore, we used epoxies with T_gs higher than body temperature (crosslinker ratios 4:10, 5:10, and 6:10) for most of the prototypes in this paper to avoid uncontrollable shape changes upon human touch. For example, if we use epoxy (3:10), the demonstrated input device (Figure 21) may undergo undesired mode change when contacted by skin. However, future work could leverage the low T_g of epoxy (3:10) for specific scenarios where temperatures lower than room temperature are available for temporary shape fixation. In this case, room temperature or body temperature can be used for triggering.

As for fabrication methods, while the embedded 3D printing approach is computer controlled, the molding method is a relatively manual process. We think that integrating computational mold design tools [3, 45, 57, 58] may enable a more controllable process and expand the design space.

10.3 Triggering Condition

The epoxy's shape memory effect requires heating for triggering, and the heating methods we demonstrated include a hot water bath, a heat gun, or resistive heating. While using a hot water bath can be convenient, easy, and playful for certain applications (e.g., kids playing with the morphing toys while bathing), its controllability may be limited. By contrast, the window shutter made with resistive heating was conveniently controlled by electricity. Future work may explore combining different stimuli to make multi-responsive systems. Furthermore, as shown in Fig.5, we point out that sequential morphing through IR light and joule heating can be attained by adding photothermal dyes and embedded conductive threads/tapes respectively,

10.4 Scalability and Recovery Accuracy

Mechanically speaking, the epoxy's restorative forces in the heated state is proportional to its cross-section area and must overcome their own weight to recover back to its permanent shape. The former scales quadratically with increasing scale while the latter scales cubically, therefore indicating that our method is less applicable to scales beyond the range (10-50 cm) explored in this work. On the other hand, fabrication precision is the only limiting factor for producing smaller (i.e., objects with micrometer-scale features) scale prototypes. Future work may consider exploring other fabrication strategies for building more fine-scaled shape memory designs, such as morphing surface textures for creating different haptic sensations, similar to that of [13]. As for the accuracy of recovery, we acknowledge that the deformed devices cannot perfectly recover to their permanent shape due to gravity, which creates a uniform load over the samples and prevents their full recovery. Yet, this issue can be compensated by overshooting the permanent shapes (i.e., compensating for the gravity-induced slack in the initial geometry), but this approach may require computational simulation and design tools. Nonetheless, the recovery accuracy improves with smaller sizes and becomes a more dominant issue when scaling up.

11 CONCLUSION

This paper presents a method for prototyping multi-state shape-changing devices by using the shape memory effects of off-the-shelf epoxy. Epoxy devices fabricated in one state can be programmed to morph into another state at a specific temperature by varying the epoxy's crosslinker to resin ratios. We demonstrate different structural primitives and fabrication strategies for designing sequentially transformed interfaces and devices that can transform between multiple shape-states. Functional components, including thermochromic ink, magnetic particles, and conductive fabrics were also explored to extend the epoxy's functionality and interaction potential. Our application examples also illustrate the method's affordance for encoding messages, providing context-aware shapes and functions, and making the living environment more responsive to human interactions. We believe this work will benefit HCI researchers in accelerating the design of shape-changing interfaces and unlock the full potential of ubiquitous computing and tangible interactions.

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